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Natural Philosophy of Protoplanetary and Planetary Discs: On the Origin and Evolution of Life

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ABSTRACT

This paper examines the four pivotal and most contentious issues within the field of biogenesis by analyzing the life-originating processes centred on protoplanetary and planetary discs. These include: 1. Geological environment; 2. Source of nutrients/initial molecules; 3. Source of energy; 4. RNA world versus metabolic world: which came first? To date, scientists have been unable to reach a consensus on these questions. Regarding geological environment, the distinct conditions within the inner, middle, snow line, and outer regions of the protoplanetary disc—including solar, cosmic, and isotopic radiation—along with the exchange of dust and gases between these zones, provided an exceptional reaction platform for prebiotic chemistry. Concerning the origin of life's food/precursor molecules, the protoplanetary disc—the stellar gas and dust disc formed during star formation—served as a crucial transitional stage linking interstellar matter to life's chemical potential. Transition metals, short- and long-lived radioactive isotopes, polycyclic aromatic hydrocarbons (PAHs), fullerenes, and the metal-organic compounds formed from these substances play a crucial role in life's composition. Analysis of meteorites reinforces the credibility of the protoplanetary and planetary discs as potential sites for the origin of life. Quantum mechanics may significantly influence the possibility of life emerging within protoplanetary discs. Regarding energy sources, the energy required for the emergence of life is quantifiable. The energy driving life's birth and evolution within protoplanetary and planetary discs can be summarized by the equations $F = ma$ and $\Delta E = \Delta m \times c^2$. These energy sources derive not only from the kinetic energy of the protoplanetary disc and interactions between dust particles, expressed by $F=ma$, but this kinetic energy can also be converted into chemical reactions, ultimately yielding prebiotic effects. Energy generated by radiation from the decay of radioactive isotopes within the protoplanetary and planetary discs, alongside energy produced by solar nuclear fusion, can be expressed by the formula $\Delta E = \Delta m \times c^2$. This energy not only generates heat but, crucially, produces radiolysis effects through solar radiation, cosmic rays, and isotope decay. These effects facilitate prebiotic chemical reactions and provide sustenance and nutrients for life within the planetary disc. Concerning the RNA-world versus metabolism-first debate, the high concentrations of PAHs and fullerenes in protoplanetary discs, coupled with their influence on the formation of aromatic amino acids and aromatic hydrophobic proteins affecting nucleic acid molecular chirality, underscore the metabolism-first theory. The discovery of Hemolithin in meteorites and its implications for RNA generation reinforce the "metabolism precedes genetics" theoretical framework. Starting from Hemolithin and primitive metabolic systems found in meteorites, lipid membrane vesicles encapsulated metabolic small molecules and informational polymers. Sustained by external energy sources, these gradually evolved into primitive systems possessing the tripartite functions of "replication–metabolism–boundary". It subsequently led to the integration of energy, protein metabolism, and membrane–genetic systems within protoplanetary and planetary discs. Ultimately, a self-maintaining and self-replicating cycle system was established within the planetary disc. The core emphasis of this paper lies in the continuity and consistency, spanning hundreds of millions of years, of the gas and molecular dust composition within the protoplanetary disc and the gases and molecules that could be generated within planetary disc planetesimals. It provided a stable energy source and an excellent sanctuary for the birth of life within the protoplanetary disc and the evolution of life within planetary disc planetesimals. The philosophical coherence that life should emerge wherever gases and molecules exist elucidates the availability of protoplanetary disc gases and molecules (such as H_2, CO, and electrons) alongside the bacteria consuming these substances within the disc's planetesimals. These gases and molecules are generated within planetary disc planetesimals by radioactive isotopes (such as 60F, 238U, ^{40}K), simultaneously producing oxygen radicals and hydrogen peroxide (e.g., H_2O_2, $\bullet OH$, $O_2\bullet^-$, NO_3^-). Thus, isotopes provided both the energy for bacterial survival and the nutrients required for bacterial metabolism, while simultaneously generating oxygen-free radicals and hydrogen peroxide that constituted a hazard to these bacteria. Consequently, bacteria acquired the capacity to resist oxygen-free radicals and hydrogen peroxide while obtaining the nutrients essential for their metabolism. The core of this process lies in the "radiation-metabolism coupling" and "radiation-metabolism co-evolution" hypotheses concerning the origin of life in protoplanetary and planetary disks. Within this theoretical framework, radiation-generated gases, molecules, and oxygen free radicals coexisted long-term with bacterial metabolism and antioxidant functions, forming the "radiation-metabolism co-evolution" model for life's origin. Only this "radiation environment-metabolism co-evolution" hypothesis can explain the survival characteristics exhibited by all bacteria and viruses we observe today. The fundamental reason why bacteria, archaea, and viruses possess exponentially higher radiation resistance than mammals lies in the direct consequence of these microorganisms' prolonged coexistence with radiation within planetary disks. Evidence from the significantly higher abundances of short-lived radioactive isotopes (SLRs) and long-lived radioactive isotopes (LLRs) in Mochison and other meteorites compared to the Earth's crust has highlighted the central theme of 'radiation-metabolism co-evolution'. Research on the Great Oxygenation Event (GOE) demonstrates that this event, dominated by cyanobacteria, represents a consistent progression from 'radiation-metabolism coupling' and 'radiation-metabolism co-evolution' to radiation-metabolism-atmosphere environmental change. Comparing sulphur isotope mass-independent fractionation (S-MIF, $\Delta^{33}S$) before and after the Great Oxygenation Event (GOE) with protoplanetary disc material reveals that the GOE effectively restored Earth's S-MIF state to the oxidized conditions present in the protoplanetary disc. further demonstrates that bacteria originating from the protoplanetary disc transformed Earth's atmosphere into the oxidized environment they inhabited within the disc – the very environment sustaining our existence today. Finally, it is discussed that the highly efficient aerobic metabolism of eukaryotes is also directly descended from the antioxidant bacteria present in protoplanetary disc planetesimals. Migratory birds and octopuses, which traverse Earth's magnetic field lines, share connections with bacterial antioxidant mechanisms and primordial genetic material. Finally, constructing a novel Tree of Life reveals that the evolutionary lineage of life differs entirely from our currently accepted model. The roots and trunk of this evolutionary tree do not originate on Earth, but rather on the planetary disc. Two branches diverge from the trunk: bacteria and archaea. The archaea branch further gives rise to a branch of eukaryotes, constituting the primary life forms on our planet today. Meanwhile, bacteria, archaea, and viruses continue to evolve both on the planetary disc and on Earth, exerting influence upon the life forms evolving on our planet.

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Introduction

Three fundamental questions of origin exist: the origin of the universe, the origin of life (OoL), and the origin of mind and consciousness. All these questions have been debated for thousands of years and are now subtopics of serious scientific research [1]. The perspective that Earth's life originated from Earth itself, also known as "endogenic origin" or "abiogenesis," is one of the mainstream theories of life's origin in the life sciences. This theory posits that life on Earth evolved gradually from inorganic matter through natural processes, without reliance on extraterrestrial life or imported organic material. However, whether it be the "primordial soup, Oparin–Hordern hypothesis"; the "Miller–Urey experiment"; the "RNA world hypothesis"; or the "hydrothermal vent theory" these represent the mainstream theories for the origin of life on Earth from within the planet itself [2-5].

An alternative theory proposed by a minority of scientists is Panspermia, which posits that life did not originate solely on Earth but is ubiquitous throughout the cosmos. Such life forms could be microorganisms or simpler organic entities [6]. Panspermia suggests that microbes or seeds of life could attach to cosmic dust, comets, meteorites, or other celestial bodies, propagating through space. These celestial bodies may have transported life from one planet in the cosmos to another, including Earth [7].

Both theories of life's origin, in my view, have made significant contributions to understanding its emergence. Scientists have elucidated the potential causes of life's origin through diverse approaches and perspectives. In 1859, Darwin published On the Origin of Species [8]. Darwin's evolutionary tree features a single trunk, representing the scientific consensus that all life forms originated from a common ancestor—a theory termed monogenesis or the single-origin theory. This theory posits that all modern organisms can be traced back to a single-celled organism that emerged on Earth approximately 3.5 billion years ago. Thus, the single trunk of the evolutionary tree symbolizes this common ancestor, while the branches and leaves represent subsequent differentiation and evolution.

Scientists are increasingly converging on a consensus that Earth's life emerged through a combination of "exogenous delivery" of organic matter and "endogenous synthesis" via chemical evolution. Exogenous delivery refers to the process by which organic compounds and prebiotic molecules from space enter Earth via celestial bodies, such as meteorites and comets. Endogenous synthesis on Earth refers to the direct generation of organic molecules and prebiotic molecules through physical or chemical processes. These include diverse energy sources such as shock waves, ultraviolet radiation, electrical discharges, and hydrothermal vents, which may have catalyzed the synthesis of more complex organic compounds from simpler molecules. These two processes complemented each other, collectively accomplishing the origin of life. However, scientists have yet to piece together the whole puzzle of life's origins. The most contentious debates among contemporary scientists regarding life's origins centre on four key points:

- Geological environment;
- Source of nutrients/initial molecules;
- Source of energy;
- The distinction between the RNA world and metabolism-first scenarios [9]. To date, no consensus has been reached on any of these issues.

The preceding article (Chemistry Analysis of Origin of Life in Protoplanetary Disks) primarily discusses the possibility of life originating in protoplanetary disks from a chemical perspective. It highlights the environmental and water paradoxes inherent in the theory of life originating on Earth [10]. It contends that life is highly improbable to have arisen on Earth or any terrestrial planet, but rather is highly probable to have emerged within protoplanetary discs. Having established the possibility of life originating in protoplanetary discs, it becomes imperative to elucidate the associated prebiotic chemical mechanisms. It would further clarify the various potential pathways for life's origin within these discs. My reasoning and hypotheses are derived from analyses of existing scientific literature.

Previous articles have discussed the origin of life within protoplanetary discs, encompassing viruses, archaea, and bacteria. Given that bacteria may have emerged within protoplanetary discs. The mechanisms related to cellular metabolism, cell membrane formation, and the establishment of cellular genetic mechanisms should be considered. The synthesis of amino acids, the generation of cell membranes, the production of RNA and DNA, and the mechanisms for translating genetic codes into proteins are all critical issues concerning the origin of life that require discussion.

This article primarily analyses the origin of life within protoplanetary discs from a prebiotic chemistry perspective, along with its evolution within planetary disc planetesimals. It also examines processes and principles related to quantum chemistry, quantum biology, cosmic environmental science, astrobiology, cosmic mechanics, and radiobiology as they pertain to protoplanetary and planetary discs. Concurrently, it discusses key issues concerning the environmental characteristics of the solar system's protoplanetary and planetary discs, as well as their relevance to the metabolism of life within the context of prebiotic chemistry.

This paper concentrates on four interrelated and most contentious themes concerning life's origin:

- the environment in which life originated;
- the source of food or initial organic molecules;

- the source of energy;
- the divergence between the RNA world hypothesis and the metabolic primacy hypothesis.

  Concurrently, two further questions are addressed, which it considers more significant:
- the establishment of life's metabolic networks, encompassing the central dogma of protein synthesis and translation, the formation of cell membranes, and the emergence of genetic systems;
- the origin of life within protoplanetary discs and the mechanisms governing its evolution within planetary disc planetesimals.

This paper begins with the atomic constituents present in the early universe, progresses through the evolution of atomic composition within the cosmos, and then examines how supernova explosions gave rise to the protoplanetary disc of the Solar System, ultimately fostering the conditions for life. The concluding section focuses on panspermia theories grounded in protoplanetary and planetary discs, specifically "planetary disc panspermia." It explores the potential structure of the tree of life based on the Solar System's protoplanetary and planetary discs.

Discussion

The Environment of Life's Origin in the Protoplanetary Disk

This article primarily explores the environment in which life originated, one of the core questions in origin-of-life theories. Essentially, it addresses the fundamental question of where life actually emerged. In the preceding article, I concluded by discussing the impossibility of life originating on Earth and the various paradoxes inherent in Earth-centred theories of life's origin. That is, life did not originate on Earth or any Earth-like planet, but rather within protoplanetary disks. Guided by this conclusion, I must now examine the conditions necessary for life's emergence within the protoplanetary disc.

These conditions encompass:

- the environmental parameters of the origin site;
- the source of food or initial organic molecules; and
- the origin of energy. These represent the core problems requiring resolution in the origin of life.

This article primarily addresses the environmental aspects of life's origin, which also constitutes the foundational question. Suppose we presuppose that life originated exclusively on Earth. In that case, we remain forever bound by the constraints of our own thinking, perpetually confined to the narrow and limited spatial and geological conditions of Earth's environment.

This section constitutes one of the most crucial parts of this article. It primarily explores how the protoplanetary disc provides the necessary conditions for the origin of life. It examines the entire environmental chain: from the initial growth of life-forming substances within the protoplanetary disc, through the emergence of life itself, to the eventual arrival of life (such as bacteria) on Earth via meteorites originating from the planetary disc. It necessitates an investigation into astrophysics, astrochemistry, protoplanetary disc physics, protoplanetary disc chemistry, and protoplanetary disc biology. If we distil this to a single critical point, it is the science of protoplanetary disc environments. Protoplanetary disc environmental science investigates explicitly the environmental conditions that facilitate the origin of life within protoplanetary discs. It stands in contrast to the various environmental hypotheses concerning the origin of life on Earth, which are currently the focus of widespread research among scientists studying the origins of life.

This chapter aims to construct all conceivable environmental systems within the protoplanetary disc that could potentially influence the origin of life there. This endeavour seeks to establish a comprehensive, logically coherent framework for protoplanetary disc biogenesis that reflects scientific reality. It lays the groundwork for future research into protoplanetary disc biogenesis by creating a self-contained scientific and theoretical system.

This paper will explore the astrophysical environment of the Solar System, particularly the decisive influence of supernova explosions on the emergence of life within protoplanetary discs; the chemistry of the Solar System's protoplanetary disc, especially the chemical conditions relevant to the origin of life; the impact of physical factors within protoplanetary discs on the emergence of life; and the potential influence of astrobiology on the origin of life within protoplanetary discs.

The Origin of Protoplanetary Discs

The origins of stars and planets are inextricably linked, both emerging from dense molecular clouds within the interstellar medium. Under the influence of gravitational forces, these molecular cloud clusters undergo collapse due to localized density increases, ultimately forming young stars. During this process, governed by the conservation of angular momentum, the collapsing material gradually spreads into a flattened, rotating structure within the equatorial plane—the protoplanetary disk [11]. This structure not only marks a crucial stage in stellar formation but also serves as the primary site for the formation of planets, comets, minor bodies, and precursor molecules for life.

The protoplanetary disc primarily consists of gas (predominantly hydrogen and helium) and dust particles, typically extending to several hundred astronomical units (AU), with a lifespan of approximately one to ten million years. During this period, dust particles within the disc undergo continuous collisions and aggregation, gradually forming embryonic celestial bodies ranging from micrometre to kilometre scale, which subsequently evolve into complete planetary systems. However, beyond its role in planetary formation, the protoplanetary disc also serves as a natural laboratory brimming with potential for complex chemical evolution. Observations and meteorite sample studies reveal that these discs are not only rich in organic molecules (such as formaldehyde, HCN, polycyclic aromatic hydrocarbons PAHs, etc.) but also contain significant quantities of transition metal elements (e.g., Fe, Ni, Co), short-lived radioactive isotopes (e.g., ^{26}Al, ^{60}Fe), and long-lived radioactive isotopes (such as potassium-40 (^{40}K), uranium-238 (^{238}U), uranium-235 (^{235}U), and thorium-232 (^{232}Th) provide catalysis and energy sources for diverse chemical reactions [12,13].

Moreover, the surfaces of dust particles within protoplanetary discs function as 'catalytic carriers', facilitating the adsorption, directed alignment, and reactive polymerization of simple small molecules. The thermal energy released by high-energy radiation (X-rays, ultraviolet, gamma rays) and radioactive decay serves as a crucial energy injection mechanism driving these reactions.

Taking the Solar System as an example, approximately 4.6 billion years ago, shockwaves from one or more supernova explosions triggered the local collapse of the molecular cloud within which the Solar System formed, subsequently giving rise to the young Sun and its surrounding protoplanetary disc [14]. During the early stages of protoplanetary disc formation, as high temperatures gradually cooled and organic compounds accumulated and differentiated, ideal conditions were created for the transition of inorganic molecules into higher-order organic molecules (such as amino acids, sugars, and nucleosides). Some models even propose that early life components, such as lipid vesicles and RNA precursors, may have formed within the protoplanetary disc itself, subsequently being 'seeded' onto the young Earth via later planetary transport or cometary impacts [15].

In summary, protoplanetary discs are not merely by-products of stellar system formation but may well serve as "chemical incubators" for life's origins. However, to comprehend "where life came from," a crucial scientific question remains unanswered: How precisely did the protoplanetary disc environment provide conditions for the precursors of life chemistry? This study will systematically explore the role and potential of protoplanetary discs in prebiotic chemical evolution by examining the mechanisms of organic molecule synthesis, metal-catalyzed reactions, the effects of high-energy radiation, and mineral surface selectivity.

Structure and Evolutionary Characteristics of Protoplanetary Discs

Protoplanetary discs constitute an indispensable component of stellar formation, exhibiting not only complex physical structures but also pronounced temporal evolution and spatial differentiation. Understanding the physical mechanisms governing protoplanetary discs holds fundamental significance for elucidating the origins and evolutionary trajectories of prebiotic chemical reactions.

Formation of the Flat Structure: An Inevitable Consequence of Angular Momentum Conservation

The flattened morphology of protoplanetary discs originates from the physical effect of angular momentum conservation during the collapse of molecular clouds. As gravity causes a molecular cloud to collapse gradually, its initial weak rotation rapidly intensifies. Material within the cloud converges towards the centre, while centrifugal forces constrain motion along the rotational axis. Consequently, matter accumulates predominantly within the equatorial plane, forming a structure that thins vertically and expands horizontally [16].

This disc, formed by the redistribution of angular momentum, is commonly referred to as an accretion disc. During the early stages of star formation, this disc continuously supplies material to the central star. Through mechanisms such as viscous forces, angular momentum is progressively transferred outward, thereby permitting the inward collapse of the material [17].

Accretion Processes and Temperature Gradient Distribution

Accretion serves as the primary mechanism for stellar mass growth while also driving the formation of complex structures and chemical differentiation within protoplanetary discs [18]. During accretion, material flows inward, releasing potential energy that is converted into heat, thereby generating a temperature gradient that decreases progressively from the center outward [19].

- Inner disc regions (<1 AU) may reach temperatures of several thousand Kelvin, where gas exists in atomic or ionized states, favouring the formation of high-temperature refractories such as calcium-aluminum inclusions (CAIs) [20].
- Intermediate zone (1–10 AU) Moderate temperatures facilitate gas molecular reactions, organic synthesis, and surface catalysis on minerals.
- Outer Disk Region (>10 AU) Temperatures drop to tens of kelvins, rich in ice, volatiles, and carbon-chain molecules, favourable for the aggregation of complex organic molecules (e.g., methanol, ethanol, PAHs).

This temperature gradient induces strong spatial dependence in material distribution, phase transitions, and chemical reaction pathways, forming a crucial backdrop for molecular complexity and the prebiotic selective formation of life.

Lifecycle and Physical Segmentation

The lifecycle of a protoplanetary disc typically spans approximately 1 to 10 million years (Myr), influenced by the combined effects of stellar radiation pressure, disc winds, photoevaporation, and the formation of planetary embryos [16]. Observations indicate that substantial quantities of dust and gas persist within the disc for one to two million years after star formation. By 5–10 million years, the gaseous discs in most systems gradually dissipate, transitioning into debris discs or vanishing entirel [21]. Structurally, protoplanetary discs can be divided into several characteristic regions [22].

- Inner disk (<1 AU): High-temperature, close to the star, forming metal oxides, silicate crystals, and evaporating volatiles;
- Middle disc (1–10 AU): Reaction conditions most favourable for complex organic chemistry and the aggregation of protoplanetary embryos;
- Near the ice line: Critical zone where water, methane, ammonia and other icy molecules condense, forming a chemical enrichment belt [23].
- Outer Disk (>10 AU): Low temperatures and high densities favour gas adsorption onto icy dust particles and promote surface chemical reactions.

Supernova-Injected Short-Lived Radionuclides and Long-Half-Life Isotopes

During the early formation of the Solar System, several short-lived radionuclides (SLRs) were detected within the protoplanetary disc, such as ^{26}Al (half-life ~0.7 Myr) and ^{60}Fe (half-life ~2.6 Myr). These radionuclides cannot be synthesized within the Sun and most likely originated from one or more nearby supernova explosions that injected material into the molecular cloud or directly into the protoplanetary disc [14]. Al provided an internal heat source for planetesimals and protoplanets, inducing the formation of hydrated minerals and organic rearrangement reactions [24]. Fe is recognized as a distinct supernova product; its presence suggests that the solar system formed in proximity to high-energy cosmic events [24]. Their decay not only delivers sustained thermal energy release over millions of years (approximately tens of kJ/mol) but also accompanies β-ray and gamma-ray radiation, potentially providing excitation mechanisms for the synthesis, cleavage, and repolymerization of organic molecule [25]. This exogenous injection mechanism enhances the chemical reactivity of the protoplanetary disc, establishing its energy foundation as a "prebiotic chemical reactor" [26].

During the early formation of protoplanetary discs, long-lived radionuclides such as potassium-40 (^{40}K), Uranium-238 (^{238}U), Uranium-235 (^{235}U), and Thorium-232 (^{232}Th) were present. These long-lived radionuclides, inherited from the nucleosynthesis of progenitor stars, became incorporated into primordial dust and mineral grains, subsequently accumulating within protoplanetary bodies as nebular material coalesced. The continuous radioactive decay of these isotopes generates significant radiogenic heating within small planetesimals that lack effective mechanisms for heat dissipation [27]. It creates locally elevated temperature zones, driving phase transitions, mineral recrystallization, and the emergence of a liquid water environment [28]. This process provides the necessary thermal energy and microenvironments for a series of prebiotic chemical reactions [29].

Distribution of Metallic Elements in Protoplanetary Discs and the Prebiotic Significance of Transition Metals

As a high-temperature, high-energy environment that persists during young star formation, the protoplanetary disc concentrates the fundamental elements CHNOPS (carbon, hydrogen, nitrogen, oxygen, phosphorus, sulphur), which constitute the essential organic molecules for life, alongside various metallic elements. These metals primarily originate from the interstellar medium, which is infused by metal-rich celestial phenomena such as supernova explosions, AGB stellar winds, and binary neutron star mergers, and subsequently become enriched within the disc through dust condensation. Evidence of extraterrestrial metallic content in meteorite samples, such as the substantial quantities of Fe, Ni, Co, Mg, and Zn detected in carbonaceous chondrites like the Allende and Murchison meteorites, further corroborates the widespread presence of metallic elements within protoplanetary discs. Among all metals, transition metals played a pivotal catalytic role in prebiotic processes due to their electronic structure and chemical versatility [30]. Firstly, transition metals exhibit multivalent properties, enabling electron transfer and facilitating redox reactions within catalytic cycles. Secondly, they form numerous stable coordination compounds, constructing catalytic microenvironments on mineral or dust surfaces. These functions remain widely conserved in modern life systems through metalloproteins, such as iron-containing nitrogenase, copper-containing respiratory chain complexes, and zinc-containing DNA polymerases, suggesting their origins may be traced back to metal-assisted reactions in early non-living environments [31].

Moreover, in recent years, transition metals (such as Fe, Ni, and Co) have demonstrated highly efficient catalytic capabilities towards hydrocarbons, ammonia, and simple nitrogen-containing organic compounds in simulated experiments, including Fischer-Tropsch-type synthesis (FTT) and Haber synthesis simulations [32]. In these experiments, metal catalysts frequently deposit upon carbonaceous or silicate dust surfaces, mimicking the environment of protoplanetary disc particles. It further supports their potential role in synthesizing substances related to early life. Thus, from the macro-scale origins of planetary evolution to the micro-scale catalytic mechanisms, transition metals within protoplanetary discs not only furnish the requisite elemental backdrop but may also establish the initial platform for the chemical evolution of life by catalyzing pivotal organic reactions.

The 'Existence Paradox' of the Miller–Urey Experiment

The Question of Life's Origin and Laboratory Verification Attempts

The question of life's origin has long been a central theme in astrobiology and the study of chemical evolution. In 1953, Stanley Miller and Harold Urey achieved the first successful laboratory simulation of "primitive Earth conditions" to synthesize amino acids. This landmark experiment demonstrated the scientific feasibility of transitioning "from inorganic to organic" [3]. However, despite its monumental significance in scientific history, the foundational assumption—that the early Earth possessed a strongly reducing atmosphere (e.g., CH_4, NH_3, H_2) —has faced serious challenges in subsequent decades. "The Miller–Urey experiment validated the chemical pathway but not the authenticity of its terrestrial environment" [33].

Prebiotic Synthesis in the Protoplanetary Disk: Re-examining the Philosophical Paradox of the Miller–Urey Experiment

The seminal 1953 Miller–Urey experiment is widely regarded as the first laboratory demonstration of amino acid synthesis in a non-biotic environment. However, the gas mixture employed—water vapour (H_2O), methane (CH_4), ammonia (NH_3), hydrogen (H_2), and carbon monoxide (CO)—was unstable in both the modern Earth and its early atmosphere. Subsequent geoscience and geogas escape models suggest the early Earth's atmosphere was more likely dominated by carbon dioxide (CO_2), nitrogen (N_2), and water vapour, constituting a neutral or mildly oxidizing environment. It does not support the strongly reducing conditions assumed in the Miller–Urey experiment. Thus, this experiment essentially simulates the more reducing conditions of protoplanetary disc-stage nebular gases within an Earth-based laboratory. Employing electrical sparks to mimic the high-energy particle or radiation sources common in space, it tests the non-biological synthesis potential of prebiotic molecules. In a sense, this presents an existential paradox: the experimental results are cited as supporting evidence for the origin of life on Earth, yet the experimental environment itself derives from non-terrestrial, cosmic-stage conditions.

Furthermore, subsequent gas-circulation variants of the experiment did synthesize a greater variety of amino acids and small organic molecules under reducing atmospheres. However, their diversity and complexity remain vastly inferior to those of the dozens of amino acids, nucleobases, fatty acids, and nucleoside precursors detected in meteorites (such as the Murchison meteorite) and asteroid samples (such as Bennu) [34,35]. It may therefore be concluded that the Miller–Urey experiment essentially validated feasible chemical pathways within protoplanetary discs, rather than prebiotic chemical pathways in the actual terrestrial environment.

From Paradox to Reality

From this "existence paradox," we uncover a novel, compelling demonstration: the Miller–Urey experiment precisely confirms that protoplanetary discs constitute an ideal environment for the origin of biomolecules. Although the Miller–Urey experiment simulated the possibility of biomolecules arising in natural settings within a laboratory, it employed the reducing gases characteristic of protoplanetary discs rather than the early Earth's neutral to slightly oxidizing atmospheric conditions. Subsequently, they further simulated the gas circulation patterns of protoplanetary discs, synthesizing additional amino acids and organic compounds. It provided further corroboration that life molecules originated in protoplanetary discs rather than on Earth. Thus, it can be said that Miller and Urey conducted the experiment correctly but drew erroneous conclusions. In subsequent chapters, I shall continue to discuss how various amino acids synthesized under different conditions by other researchers—which, in fact, do not exist on Earth—actually originate from processes initiated within the protoplanetary disc.

The Role of Cosmic Dust in Prebiotic Reactions within the Protoplanetary Disk

Types of Protoplanetary Disk Dust Particles and Their Surface Chemical Activity

Cosmic dust within protoplanetary discs comprises a diverse array of particle types, including silicate grains, carbonaceous particles, and ice grains coated with organic matter. These dust particles typically consist of a hard inorganic core and an enveloping layer. For instance, a typical interstellar dust particle may feature a silicate or carbonaceous core, with its surface coated by ice (water, carbon dioxide, etc.) and a thin film of complex organic compounds [36]. Different dust particle types exhibit distinct surface chemical reactivity:

Silicate Dust (Such as Olivine, Pyroxene, and other Fe/Mg-rich Silicates)
Contains doped transition metal elements (e.g., Fe, Ni), whose surfaces can catalyze crucial synthesis reactions at elevated temperatures [37]. Experiments demonstrate that iron-rich silicate powders, akin to those condensed in the solar nebula, can simultaneously catalyse the Fischer-Tropsch synthesis (converting CO and H_2 into hydrocarbons and water) and the Haber synthesis (converting N_2 and H_2 into NH_3) under conditions of 500–900 K. Remarkably, when CO, N_2, and H_2 act together on this dust catalyst, nitrogen-containing organics such as methylamine and acetonitrile can also form. It suggests that transition metal sites on silicate dust surfaces can act as catalytic centers, facilitating the synthesis of small organic molecules, such as amino acid precursors. Furthermore, silicate dust can adsorb and mobilize atoms at low temperatures, facilitating their reaction. For instance, at ~10 K, two adsorbed hydrogen atoms can combine on silicate or ice surfaces to form H_2 molecules, with the dust particle acting as a "third body" absorbing excess reaction energy. This surface-binding/diffusion mechanism is crucial for H_2 formation in space, as three-body collisions are exceptionally rare in the sparse gas phase.

Carbonaceous Dust (such as Amorphous Carbon, Graphite, and Carbon-Rich Particles) Possesses surfaces rich in carbon-carbon bond structures. While these do not provide the typical catalytic activity of transition metals, they serve as platforms for the formation and polymerization of organic molecules. Within the interstellar medium, small molecules can adsorb onto carbonaceous dust surfaces and undergo radical reactions, progressively forming more complex hydrocarbon networks. For instance, researchers propose that complex organic molecules such as polycyclic aromatic hydrocarbons (PAHs) may partially originate from stepwise polymerization on dust particle surfaces. Under high-energy radiation, functional groups and unsaturated bonds on carbonaceous dust surfaces readily form radical centers, thereby promoting reactions such as carbon chain elongation and the formation of aromatic rings. Despite lacking metallic active sites, the surfaces of carbonaceous particles can still participate in the formation of organic molecules through physical adsorption and radical mechanisms. Spectroscopic and experimental evidence indicate the presence of complex organic solids, known as "resins," within interstellar dust. These resins are hypothesized to form through the photopolymerization of hydrocarbons on cold particles under ultraviolet irradiation.

Organic/ice-Encapsulated Particles
Constitute a prevalent dust form in molecular clouds and outer disc regions. At low temperatures, dust surfaces accumulate frozen layers (H_2O, CO, CH_3OH, NH_3, etc.) and encapsulate simple organic compounds. Cosmic rays and ultraviolet light penetrating this ice induce extensive chemical reactions within. As ice acts as a dielectric medium, high-energy particles and UV radiation ionize or dissociate molecules within the ice, generating highly reactive radicals (e.g., H·, OH·, NH_2·, CN·, etc.) [38]. These radicals can migrate and recombine within the low-temperature ice matrix on dust surfaces. Despite temperatures of approximately 10 K, their low-energy barrier recombination reactions proceed spontaneously. Consequently, more diverse and complex molecules are synthesized on the surfaces of ice particles. For instance, laboratory simulations demonstrate that continuous UV irradiation of mixtures such as water ice and methanol at 10 K can yield simple organic molecules, including H_2, H_2O, formaldehyde (H_2CO), and methanol (CH_3OH). More complex components emerge as the ice undergoes radiation and gradual heating: organic coatings (rich in CHON elements) form on dust particles. When temperatures rise to tens or hundreds of K, these radiation products can rearrange or desorb into larger organic molecules. Modelling studies indicate that frozen dust particles, during their inward migration from the outer disc in the solar nebula, repeatedly undergo low-temperature UV irradiation and mild heating. This process enables the conversion of ice and organic matter on their surfaces into complex organic products [39]. These products include numerous life-related molecules, leading to the recognition of ice/organically coated dust as one of the 'hotbeds' for synthesizing prebiotic molecules such as amino acids and nucleobases.

The aforementioned diverse dust particle types furnish varied reaction platforms for prebiotic chemistry: silicate and metal sulphide particles offer mineral-like catalytic functions (utilizing transition metals to catalyze key reactions). In contrast, carbonaceous and organically coated particles accumulate and transform simple molecules into more complex organics via adsorption and radical mechanisms.

Chemical Reaction Platforms in Protoplanetary Discs
The aforementioned diverse types of dust particles provide varied reaction platforms for prebiotic chemistry silicate and metal sulphide particles offer mineral-like catalytic functions (utilizing transition metals to catalyze key reactions). Scientists often cite Earth's crucial chemical reaction platforms for life's origin. However, I contend that the "F-S World" appears not to reside on Earth, but rather within the protoplanetary disc. Carbonaceous and organically coated particles accumulate and transform simple molecules into more complex organics through adsorption and radical mechanisms. Similarly, the analysis above suggests the Aromatic World Hypothesis is more likely to have been realized within the protoplanetary disc.

Excitation and Synthesis of Molecules on Protoplanetary Disk Dust by Cosmic Radiation
Within protoplanetary discs and the interstellar medium, dust particles are immersed in an environment saturated with high-energy electromagnetic radiation and particle radiation. Young stars and the cosmic background emit X-rays, ultraviolet radiation, and high-energy cosmic ray particles, all of which exert a significant influence on the chemistry occurring at the dust surface [36].

Specifically
Ultraviolet (UV) Radiation
Ultraviolet (UV) radiation can be directly absorbed by molecules on dust surfaces, breaking chemical bonds to generate free radicals or ions. Dust particles act as both "generators" and "carriers" of free radicals. At extremely low temperatures (10–50 K), fragments produced by UV photolysis cannot escape rapidly and remain trapped within the ice or organic matrix on the dust surface. These fragments can rearrange to form new covalent bonds. When two free radicals encounter each other on the confined dust surface, they readily couple to form more complex neutral molecules. For instance, experiments confirm that when simulated interstellar ice (a mixture of H_2O, CO, CH_4, NH_3, etc.) is exposed to vacuum UV irradiation below 77 K, diverse complex organic residues are generated. Upon heating and hydrolysis of these residues, amino acids (such as glycine and alanine) can be detected [40]. It indicates that UV-induced "amino acid precursors" formed within the ice subsequently convert into amino acids under mild thermal treatment. Similarly, UV irradiation on ice rich in simple

organic compounds, such as HCN and CH_3OH, can introduce nitrogen-containing functional groups, synthesizing prebiotic molecules like aminonitriles and amides. In nebular environments, intense UV exposure within the inner disc regions near young stars triggers extensive photolysis-synthesis cycles on the surfaces of organic ice-bearing dust particles. This process is recognized as a natural by-product of planetary system evolution, yielding complex organic molecules [39].

Higher-Energy Photons

Such as X-rays and gamma rays, possess greater penetrating power, enabling them to penetrate deep into dust grains or thick ice layers to induce radiolysis. High-energy photons generate secondary electrons and fluorescence within solids, thereby breaking molecular bonds like UV radiation. Due to their deep penetration, molecular fragments and free radicals also form within ice. These can be stored long-term within ice lattices at low temperatures; when the environment warms slightly (e.g., from 10 K to 30–40 K), some atoms and free radicals gain mobility and react, rapidly synthesizing more stable macromolecules. Both theoretical and experimental evidence support the accumulation of a "frozen" radical reservoir within ice, induced by cosmic ray-induced internal radiation. As temperatures rise, these radicals interact abruptly, forming molecules such as methanol, ethanol, simple sugars, and even larger compounds [41]. Thus, even deep-cold dust far from light sources can gradually accumulate complex organic matter under sustained bombardment by cosmic rays.

Direct Collisions of High-Energy Particles (Cosmic Rays, Protons, etc.)

With dust particles similarly induce molecular excitation and dissociation. On the one hand, fast heavy-ion impacts generate track-induced radiation along their path, triggering cascading molecular fission and ionization. On the other hand, high-energy protons/electrons deposit energy within ice, acting similarly to gamma rays. Experiments bombarding 10 K simulated ice with MeV protons have confirmed that particles irradiating H_2O, CO, NH_3, and other compounds in ice generate a diverse range of volatile organic compounds. Residual, less volatile organic matter releases amino acids (such as glycine and alanine) upon warming to room temperature and undergoing hydrolysis [40]. These findings indicate that cosmic rays and UV radiation collectively constitute the most potent energy sources for organic synthesis in space. Unlike in solution, where radicals are readily quenched, radicals exhibit longer lifetimes and higher migration probabilities in vacuum and on solid surfaces. Consequently, radiochemistry emerges as a primary driving force for the formation of organic molecules on interstellar dust. As one astrochemist observed: "Chemical reactions on dust particle surfaces play a pivotal role in the chemistry of nascent planets; much of the chemistry of interstellar dust particles is driven by radiation (particularly UV, X-rays, and cosmic rays)".

The 'Micro-Chemical Reactor' Function of Protoplanetary Disk Dust

Through the mechanisms mentioned above, high-energy radiation induces radicals and ions on dust surfaces. These intermediates then recombine to form more complex bonds. The result is that dust acts as a "microscopic chemical reactor" within intense radiation environments, facilitating reactions ranging from the simplest synthesis of H_2 and H_2O to the stepwise formation of complex organic molecules. In the context of prebiotic chemistry, this implies that key molecules such as amino acids, nucleobases, and simple sugars can be naturally synthesized through radiation pathways within dust in the non-living cosmic environment.

Impact of Short-Lived Radioisotopes on Protoplanetary Disk Dust Heating and Reaction Environments

Within the young protoplanetary nebula of the early Solar System, substantial quantities of short-lived radioactive isotopes (such as^{26}Al and ^{60}Fe) were incorporated into solid particles and planetesimals. Their decay processes exerted two significant influences on chemical evolution: internal heating and radiation sources. Among these 26Al (with a half-life of approximately 0.72 million years) stands as the most prominent example.

Radioactive Decay Heating

26 Al decay releases high-energy alpha particles and gamma rays, primarily converting energy into heat. It has profound implications for larger dust aggregates and even planetary embryos. Within the first few million years of solar system formation, Al-rich (26) Al-rich minor bodies were heated internally above the melting point of ice, thereby generating conditions conducive to liquid water [42]. Geological evidence suggests that the parent asteroids of carbonaceous chondrite meteorites underwent radioactive heating during their early stages, causing internal ice to warm and melt, thereby producing liquid water and enabling hydrothermal chemical processes. Consequently, (Al provided a hot-water reactor on primordial small bodies: water interacting with metallic minerals and organic matter within dust could facilitate a series of aqueous chemical reactions. For instance, within the hydrothermal environments of these parent bodies, simple small molecules (such as formaldehyde and ammonia) can condense or transform into more complex organic precursors. Experimental simulations support this: incubating solutions of formaldehyde and ammonia under heated conditions generates amino acid precursor compounds (requiring hydrolysis to release amino acids). Yields further increased when gamma-ray irradiation was applied concurrently with heating, indicating a synergistic effect between ionizing radiation from radioactive decay and thermal energy. Recent studies have revealed that simulated systems subjected to irradiation followed by heating produce amino acid precursors more efficiently than those treated with heating alone or with different treatment sequences. It is hypothesized to arise because radiation generates oxygenated organic radicals and carbonyl compounds within solutions or ice, via a Maillard-type process, whereupon heat subsequently promotes rearrangement of these intermediates into more complex products. In other words, (26) Al decay simultaneously provides two essential elements: internal energy (heating enhances reaction kinetics) and radiochemistry (creating reactive species).

Evolution of the Chemical Environment within Asteroids/Dust Bodies

The decay heat of ^{26}Al drives thermal evolution within many early planetary bodies. For micrometeoroids hundreds of metres in diameter, model calculations indicate ^{26}Al decay dominates internal heating, potentially causing internal melting or differentiation (e.g., molten iron cores, asteroidal magmatism). Whilst individual micrometre-scale dust grains cannot accumulate sufficient heat alone, when these coalesce into parent bodies several kilometres in size, the energy from 26Al decay is locally deposited, driving water-rock reactions and thermal transformation of organic matter. For instance, a significant proportion of amino acids detected in carbonaceous meteorite parent bodies may have formed during such hydrothermal stages through reactions of simple precursors (HCN, NH_3, aldehydes, etc.), rather than having been generated on Earth [43]. Decay heating can also induce thermal pyrolysis and recombination of organic inclusions. For instance, complex organic matter within carbon-rich dust partially degrades and recondenses at ~100–200° C, yielding more polar organic compounds that enter the aqueous phase and become incorporated into the parent body's minerals.

Radiation Effects

Short-lived nuclides emit ionizing radiation alongside heat. 26Al decay emits 1.3 MeV beta particles and 1.8 MeV gamma rays, which can ionize surrounding matter. Within the parent body, rock absorption of gamma rays is relatively limited yet sufficient to generate local ion pairs and free radicals. For instance, dust particles containing Al are themselves bombarded by their decay γ-rays (and radiation from the decay product Mg), inducing cosmic ray-like chemistry. However, compared to external cosmic ray sources, the radiation flux from internal radioactive sources is lower and has a limited range of action; thus, their primary contribution remains the thermal effect. Within enclosed parent bodies, radioactivity provides a low-dose radiation background that persists for millions of years, potentially facilitating the slow modification of organic matter, such as promoting the formation of aromatic structures and increasing oxidation states. Meteorite studies suggest that certain organic components may have undergone prolonged irradiation by radioactive substances, resulting in distinctive chemical signatures.

^{60}Fe (half-life approximately 2.6 Myr) was also present in the early solar system, providing additional heat through decay (primarily $\beta^-$and γ-ray emission). Whilst ^{60}Fe's heat production alone was insufficient to melt large bodies, it acted synergistically with ^{26}Al heating in iron-rich asteroids. Collectively, these short-lived radioactive sources shaped the chemical environment of early dust/planetary discs: water released from ice provided a medium for organic synthesis, thermal energy drove reactions, and radiation created bioactive intermediates. It represents one of the key prebiotic chemical scenarios beyond Earth. Researchers note that such natural chemical pathways could have universally generated the building blocks of life throughout the solar system and potentially other planetary systems [37].

Comparison of Mineral Surface Reactions in Early Earth's Environment with Protoplanetary Disk Dust Platforms

Compared to protoplanetary discs rich in cosmic dust, the early Earth environment exhibited distinct differences in terms of "surface platforms" suitable for prebiotic chemistry. This disparity restricted nearly all chemical pathways to Earth's native conditions, further substantiating the origin of life's building blocks within protoplanetary discs:

Primordial Atmospheric Composition and Reductive Potential

Modern research suggests the Taecenaean Earth's atmosphere was dominated by CO_2, CO, and N_2, with minimal hydrogen and methane, presenting an overall neutral-to-oxidizing environment [37]. Within such conditions, the classical Miller-Urey reaction (relying on strongly reducing gases like CH_4 and NH_3) proved highly inefficient. Laboratory discharge and illumination experiments demonstrate that gas phases rich in CO_2 and poor in methane struggle to synthesize reducing organic compounds, such as amino acids, aligning with the primordial Earth conditions. Concurrently, terrestrial pathways for reducing N_2 to NH_3 (such as lightning, volcanic activity, or submarine hydrothermal vents) exhibit a limited yield, which is insufficient to supply substantial quantities of reducing nitrogen compounds. By contrast, the protoplanetary disc dust environment provides the missing link. Within the solar protoplanetary nebula, transition metals like iron and nickel catalyze the conversion of CO_2/CO into hydrocarbons (such as CH_4) and N_2 into ammonia (NH_3) under low-oxygen conditions. Nitrogen-containing organic molecules (e.g., methylamine, acetonitrile) can also form directly on dust surfaces. These molecules, which could have served as precursors to life on Earth, were challenging to produce indigenously due to Earth's lack of a dust-catalyzed environment. In other words, the early Earth may have lacked a widespread reductive catalytic platform for efficiently generating certain fundamental organic molecules. Cosmic dust, however, had already "pre-synthesized" nearly all the foundational molecules for life during the protoplanetary disc nebula phase, subsequently delivering them to Earth via meteorites and micrometeorites.

Abundance and Forms of Utilizable Elements

The utilizable forms of key life-essential elements (such as C, N, P, S) in Earth's primordial crust were severely limited. Phosphorus primarily existed as insoluble phosphate minerals, nitrogen predominantly as inert N_2 gas, carbon was largely locked within CO_2, and sulphur was mainly present as stable sulphates. These forms were not "friendly" to inorganic chemistry. Life subsequently evolved complex enzyme systems to access them, mechanisms that were absent in the prebiotic stages. In contrast, protoplanetary disc dust and meteorites enriched these elements in reactive forms: for instance, phosphides (such as Fe_3P, which generates soluble phosphates upon entering water), organic nitrogen compounds (ammonia, nitriles), reduced carbon (methanol, hydrocarbons), and free sulphides. Research indicates that certain nutrient elements, which are severely deficient in Earth's surface layers, are present in protoplanetary disc dust at concentrations several orders of magnitude higher than in the crust. It suggests that life was delivered as "chemical fertilizer" by falling cosmic dust/meteorites. In contrast, the local raw material concentrations on early Earth were insufficient to readily assemble precursors of biomolecules such as nucleotides and fatty acids.

Types and Properties of Mineral Surfaces

Although solid surfaces existed in Earth's early days—such as volcanic rocks, clay minerals, and metallic sulphides—and are thought to have participated in prebiotic chemistry (e.g., clay minerals adsorbing organic matter and catalysing polymerisation; pyrite FeS+NiS catalysing CO_2 reduction in hydrothermal vents), However, compared to cosmic dust, Earth's mineral surfaces operate under distinct conditions—including liquid water environments and higher gravitational forces—resulting in different chemical pathways. In aqueous solutions, free radicals are readily quenched, with reactions predominantly following solution chemistry mechanisms rather than surface solid-state mechanisms. Cosmic dust, typically existing in a vacuum or gas phase, enables surface reactions via heterogeneous catalysis and radiochemistry—processes that are difficult to replicate on Earth's surfaces. For instance, processes like H_2 formation and methane synthesis occurring on dust surfaces require high temperatures or catalysts in the Earth's atmosphere. Similarly, PAH synthesis in the interstellar medium follows a radical surface condensation pathway. In contrast, on Earth, aromatic hydrocarbons are predominantly produced by the combustion of organic matter or high-temperature processes. Moreover, dust particles are tiny (on the submicron scale) and occur in vast quantities, yielding an immense total surface area that provides ample opportunities for molecular reactions. In contrast, available mineral surfaces on Earth (such as rock fissures or coastal clays) possess relatively limited total surface area and are often covered by water or organic films that inhibit reactivity. Consequently, specific prebiotic reaction pathways possible in space (such as ultraviolet-driven amino acid synthesis on icy surfaces at low temperatures) either cannot occur under terrestrial conditions or proceed with extremely low efficiency. This constraint on Earth's indigenous chemical processes necessitated the delivery of pre-synthesized "building blocks" to the planet's surface via meteorites and dust. Consequently, scientists hypothesize that most key molecules for life—such as amino acid and nucleotide precursors—were likely "exogenously synthesized and endogenously supplied," rather than originating from Earth's own chemistry [44].

The Protoplanetary Disc as the Optimal Environment for Life's Origins

Overall, the early Earth lacked the pervasive diffuse catalytic particles and radiation conditions prevalent in protoplanetary discs, which partly contributed to the scarcity of initial organic synthesis on Earth. Consequently, Earth's prebiotic chemistry likely relied heavily on two compensatory pathways: first, minimal synthesis occurring in non-conventional environments (such as atmospheric lightning discharges, meteorite impacts, or volcanic hydrothermal vents), which may have been absent; second, cosmic delivery (via micrometeorites, meteors, and cometary material) supplying preformed organic molecules. Decades of meteorite research support the latter pathway—many building blocks of life molecules arrived on Earth in extraterrestrial form, precisely matching the chemical capabilities of protoplanetary discs, cosmic dust, and parent asteroids. It also represents the optimal environment for the origin of life in the cosmos.

Recent Discoveries from Experimental Simulations of Protoplanetary Disks and Meteorite Analyses

Recent years have seen experimental simulations of protoplanetary disc cosmic dust chemistry and analyses of carbonaceous meteorites continually revealing evidence and details of prebiotic molecule formation in space.

Dust Catalysis Synthesis Experiment

The seminal experiment by Hill and Nuth (2003) cited above demonstrated the catalytic potential of cosmic dust [37]. Using ferrosilicate powder resembling solar nebular condensates, they passed primordial gas mixtures (CO, N_2, H_2) through the catalyst bed at 500–900 K, successfully synthesizing simple molecules such as methane and ammonia, as well as nitrogen-containing organics (e.g., methylamine, acetonitrile). This outcome provides direct evidence for the simultaneous generation of hydrocarbon and nitrogen-containing molecules in exoplanetary environments, supporting the "pre-processing" role of dust within protoplanetary discs in the Solar System. Recent expansions of such research—including simulations with more complex gas compositions and diverse mineral catalysts—demonstrate the transformative capacity of protoplanetary disc dust surfaces on inert small molecules, such as CO_2 and N_2.

Radiation Simulations on Cryogenic Ice

To model interstellar media and the outer regions of the solar protoplanetary disc, numerous experiments employ ultra-high vacuum cryogenic apparatus. Mixed-ice thin films are deposited onto cold fingers (10–80 K), subsequently irradiated with UV lamps or ion beams. Notable experiments by Bernstein et al. and Muñoz Caro et al. irradiated ice containing H_2O, CH_3OH, NH_3, and HCN components with UV light. The residual organic matter yielded multiple amino acids (including glycine, alanine, serine, etc.) [43,45,46]. These amino acids appeared in racemic form and exhibited deuterium enrichment, mirroring amino acid signatures in meteorites. It confirms laboratory-synthesized amino acids originate abiotically, potentially mirroring processes in the outer protoplanetary disc environment. Holtom et al. similarly obtained amino acids by bombarding ice-like formulations with high-energy electrons (simulating cosmic rays) [47]. Collectively, these experiments confirm that the "UV/radiation- + -ice" pathway can synthesize dozens of amino acids and other organic molecules. Recent experimental refinements have enhanced analytical sensitivity and broadened the range of detectable products. For instance, research by the German Aerospace Centre and others has detected dipeptides (two amino acids linked) and phosphorus-containing organic compounds formed upon ice illumination, suggesting that primitive condensation polymerization reactions may even occur on dust-ice membranes within protoplanetary discs.

Radioisotope Simulation Experiments

Addressing hydrothermal radiation environments within meteorite parent bodies, recent research designed simulations combining gamma-ray irradiation and heating [42]. They subjected simulated solutions of formaldehyde, methanol, and ammonia to low-dose γ irradiation followed by heating. The final products yielded typical amino acid precursors, exhibiting spectral characteristics reminiscent of Maillard reaction products. Notably, the "radiation-then-heating" sequence demonstrated significantly higher efficiency in producing amino acid precursors than the "heating-then-radiation" approach. It suggests that within the radioluminescent interior of 26Al asteroids, radiation from radioactive sources can synergize with thermal effects to synthesize biomolecules more efficiently. This finding aligns with the formation mechanisms of certain organics (such as nitrogen-containing brown macromolecules) observed in meteorites, offering microscopic evidence for these processes.

Latest Identification of Meteorite Organics

With advances in analytical techniques, scientists continue to discover new organic constituents within meteorites, many directly related to biomolecules. Among these, amino acids were first identified in carbonaceous chondrites (such as the Murchison meteorite that fell in 1969) as early as the 1960s. To date, over 80 amino acids have been identified in Murchison, including 12 of the 20 commonly used in proteins, alongside numerous non-protein amino acids [48]. These amino acids exist as racemic mixtures and exhibit anomalous isotopic ratios (such as elevated D/H and N), confirming their non-biological origin and likely interstellar/nebular provenance. More astonishingly, recent analyses have identified all five nucleic acid bases within meteorites: adenine (A), guanine (G), uracil (U), cytosine (C), and thymine (T). For many years, only A, G, and U had been reliably detected in meteorites, while C and T remained unconfirmed due to their extreme susceptibility to degradation. In 2022, a team from Hokkaido University in Japan successfully detected trace amounts of C and T from multiple carbonaceous meteorites using a mild cold-water extraction method. It marked the first time all five DNA/RNA bases had been "collected" within meteorites [44]. Simultaneously detected were multiple structural isomers of these bases, further confirming they did not originate from terrestrial contamination. Additionally, in 2019, scientists identified ribose (the pentose sugar that forms RNA) and related sugars within meteorites, indicating that both the sugar and base components of nucleotides can be supplied by space chemistry. Meteorites also harbour abundant organic acids: diverse carboxylic acids, including monocarboxylic and dicarboxylic acids (i.e., fatty acid chains), were reported as early as the 1970s [49]. For instance, a series of fatty acid anions of varying chain lengths was detected in the Murchison and Murray meteorites, with some presumed to exist as sodium or magnesium salts. These fatty acids constitute the fundamental building blocks of cell membrane lipids, suggesting extraterrestrial chemistry may have laid the groundwork for assembling primordial membrane structures. Preliminary analysis of Benu asteroid samples returned by NASA's OSIRIS-REx mission (2023) corroborates these findings: Benu samples contain fourteen protein amino acids and all five nucleic acid bases, at concentrations exceeding those found in known meteorites [50]. It undoubtedly lends further credence to the notion that asteroid/comet material seeded Earth with the building blocks of life. It also provides additional evidence supporting the theory that primordial life may have originated from the protoplanetary disc.

Chiral Bias and Advanced Molecules

The chiral bias of organic molecules and products of multi-step reactions remains a current research focal point. Amino acids in meteorites predominantly exist as racemic mixtures. However, certain meteorites, like Murchison, exhibit a slight L-enantiomer excess in a few amino acids, potentially linked to optically polarized radiation from nebulae. Experimentally, reactions induced on dust surfaces under circularly polarised UV light also yielded amino acid products with slight chiral excess. It suggests that cosmochemical processes not only generate diverse molecules but may also pre-imprint molecular chirality—a hallmark of life—onto specific precursors. Another advancement involves detecting evidence of complex organic macromolecules, such as the presence of insoluble organic matter (IOM) in meteorites, whose structure resembles highly cross-linked organic polymers. Recent synchrotron radiation and mass spectrometry studies are progressively deciphering the structural units, revealing the coexistence of aromatic rings, heterocycles, and long-chain structures. These macromolecules are hypothesized to have formed through the gradual polymerization of simple molecules via radiation and heat on parent asteroids. Although abiotic pathways have yet to simulate genuine RNA or peptide chains, these findings indicate that each step from monomers to oligomers is feasible in space.

In summary, the latest evidence from laboratory simulations and meteorite analyses strongly supports the notion that protoplanetary disc dust particles functioned as catalytic factories and transport vehicles for key prebiotic molecules. Whether through radical surface reactions that form simple organics in cold outer protoplanetary discs or the synthesis of complex molecules within radiatively heated planetesimals, dust played a crucial role in the chemical evolution of life's building blocks. The absence of such platforms in Earth's early stages implies that virtually all life's raw materials likely originated from protoplanetary disc chemistry and were delivered by protoplanetary disc dust/meteorites. This insight broadens our perspective on the environment of life's origin: life's starting point may not have been confined to a planetary surface niche, but instead began within the chemistry of dust clouds pervading the protoplanetary disc, commencing during the formation of planets.

Aromatic World Hypothesis

In the preceding discussion, I concluded that life and life-bearing matter within the cosmos originate from stellar disks or protoplanetary disks. Even where no planets form within a stellar system's protoplanetary disk, life or life-bearing matter may still emerge within that disk [10]. Unlike our solar system, this nascent life or life-bearing matter, lacking planets to accrete onto, is ultimately blown by stellar winds into the interstellar medium (ISM) as cosmic dust. There, it endures cosmic radiation from stars and star systems. Life or complex biomolecules originating from protoplanetary or protostellar discs are destroyed within cosmic dust, such as nucleobases, amino acids, and sugars. Molecules resistant to cosmic radiation, such as polycyclic aromatic hydrocarbons (PAHs), can be detected in the gas phase by infrared and microwave spectroscopic telescopes. They are widely observed in interstellar dust, cometary dust, interplanetary dust, and circumstellar dust [51]. Here, we note that cometary dust, interplanetary dust, and circumstellar dust all bear a direct connection to the protostellar or protoplanetary discs from which stars are born. Similarly, PAHs within interstellar dust can only be said to have been blown by stellar winds from the protostellar or protoplanetary discs, where they originated, into the more distant interstellar space [52].

How are PAHs Originating from Protoplanetary Discs Detected? How, then, can we prove that these PAHs originate from protoplanetary discs? Extensive evidence indicates the widespread presence of PAHs, as observed across different spectral bands by telescopes studying stellar clouds or protoplanetary discs. For instance, the Spitzer Infrared Spectrometer (IRS) has detected characteristic PAH emission in multiple protoplanetary discs, particularly around Herbig Ae/Be stars [53]. Studies of discs around T Tauri and Herbig Ae/Be stars reveal a PAH detection rate as high as 60% for Herbig Ae/Be stars, compared to a lower rate of approximately 10% for T Tauri stars [54]. It indicates the widespread presence of PAHs within these discs, particularly around higher-mass stars. The Mid-Infrared Instrument (MIRI) aboard the James Webb Space Telescope (JWST) provides higher-resolution observational capabilities, further confirming the presence of PAHs within protoplanetary discs. For instance, Sturm et al. utilized JWST/MIRI to observe the edge disc of HH 48 NE, detecting multiple PAH emission features, which indicates that these molecules are predominantly located within the disc's surface layer [55].

Furthermore, Arulanantham et al. detected PAH emission at 11.3 micrometres while studying the edge-on disc of the T Tauri star Tau 04202, providing additional evidence for the widespread presence of PAHs within protoplanetary discs [56]. Ground-based observations using the VISIR mid-infrared instrument on the VLT have also successfully detected PAHs. For instance, Yoffe et al. employed VISIR to observe the protoplanetary discs around eight Herbig Ae stars, resolving PAH emission features in five discs. They found that these emissions exhibited spatially centred or annular distributions, suggesting specific distribution patterns for PAHs within the disc structure [57].

Comparing PAH Abundances in Protoplanetary Discs Versus Terrestrial Environments

In the interstellar medium (ISM) of the Milky Way, approximately 10% to 20% of carbon exists in the form of polycyclic aromatic hydrocarbons (PAHs) [58]. Within protoplanetary discs, and particularly in carbonaceous chondrites (such as the Murchison meteorite) and comets (such as Halley's Comet and Comet 67P/Churyumov–Gerasimenko), PAHs and PAH-containing material can constitute up to several tens of per cent of the total organic content [59]. In contrast, the natural abundance of PAHs in Earth's environment is extremely low, primarily originating from combustion (such as forest fires and volcanic activity), industrial emissions, human activities, or minor meteorite inputs [60]. The abundance of PAHs in protoplanetary discs exceeds that on Earth (including that from fossil fuel combustion) by more than 100,000-fold. If PAHs play a crucial role in prebiotic chemistry, the contrast between their abundance in protoplanetary discs and terrestrial environments provides compelling evidence. Below, we discuss the relationship between PAHs and the building blocks of key life components: cell membranes, amino acids, and nucleobases. This further supports the notion that life on Earth originated from protoplanetary discs.

Potential Relationship Between PAHs and Life's Constituents

Polycyclic aromatic hydrocarbons (PAHs) are ubiquitous organic molecules in the cosmos, potentially playing a vital role in the origin of life. Their potential connections to cell membrane composition and other fundamental biomolecules (such as amino acids, bases, and ribose) are outlined below.

Relationship between PAHs and Cell Membrane Composition

In the early protoplanetary disc environment, the conventional membrane model involving lipid bilayers may not represent the earliest biological membrane structure, as such lipid membranes exhibit poor stability under primordial harsh conditions. Conversely, PAHs possess high chemical stability, are ubiquitous in the cosmos, and can form naturally under interstellar or protoplanetary disc conditions, making them a potential primordial membrane material [61].

Advantages of PAHs as Membrane Constituents

High stability: PAHs possess robust structures capable of withstanding harsh environments such as ultraviolet radiation, cosmic rays, and high temperatures, rendering them far more suited to the extreme conditions of early Earth than lipids. Hydrophobicity and self-assembly properties: PAH molecules can form stable molecular stacks or microcapsule structures via π-π stacking interactions. This self-assembled structure resembles the enclosed architecture of cell membranes, potentially providing the isolating environment required for early life forms [62]. The hydrophobicity and planar structure of PAHs may mimic the hydrophobic tails of lipids in modern cell membranes, aiding in the formation of primordial membrane structures [63]. Experiments demonstrate that PAHs can self-assemble into micelle or vesicle-like structures in aqueous environments, providing templates for the formation of primordial membranes [64]. Under laboratory simulation conditions, PAHs have been shown to form stable vesicular structures or membrane-like aggregates capable of stably housing other primordial biomolecules (such as nucleotides or amino acids) [65]. As precursor molecules: Oxidized or hydroxylated derivatives of PAHs (e.g., quinones) may participate in synthesizing more complex membrane components. For instance, quinones engage in electron transport chains within modern cell membranes (e.g., mitochondrial inner membranes), and their structures may be evolutionarily related to PAHs. Hydrophilic/Hydrophobic Balance: Whilst PAHs are inherently hydrophobic, certain oxidized or modified PAH molecules exhibit amphiphilic properties. This characteristic facilitates the formation of membrane-like structures within aqueous environments.

Theories propose that PAHs in the interstellar medium may have co-evolved with lipid precursors (such as fatty acids), generating more complex membrane structural components through photochemical reactions. PAHs within protoplanetary discs may have co-evolved with lipid precursors (such as fatty acids), generating more complex membrane structural components through photochemical reactions. Widespread presence in protoplanetary disc environments: PAHs are extensively found in interstellar clouds, protoplanetary discs, meteorites (such as the Murchison meteorite), and comets. They provide a rich source of prebiotic material, readily accessible to early Earth for the subsequent emergence of life.

Commonality of π-π Stacking and Hydrophobic Effects Between PAHs and Aromatic Amino Acids/DNA/RNA Bases

During the origin of life, aromatic molecules (e.g., PAH derivatives) share similar planar aromatic ring structures with modern aromatic amino acids (phenylalanine, tyrosine, tryptophan) and the bases of DNA/RNA [66,67]. π-π stacking: This interaction arises from the mutual attraction between π electrons on aromatic rings, leading to stable molecular structures formed through perpendicular or staggered stacking. In DNA, nucleic acid bases stack perpendicularly to stabilize the double helix structure [68]. In proteins, phenylalanine, tyrosine, and tryptophan contribute to stabilizing the tertiary structure through analogous aromatic stacking interactions. Hydrophobic effect: The hydrophobic regions of aromatic molecules tend to aggregate, thereby avoiding contact with polar water molecules [69]. This effect was crucial in the early stages of life, providing an isolated non-polar environment conducive to molecular self-organization.

π-π Stacking and Hydrophobic Effects in Modern Archaea and Thermophiles

Modern Archaea and Thermophiles inhabit extreme environments such as high temperatures or pressures. Their protein structures often enhance rigidity and thermal stability by increasing the proportion of aromatic amino acids (phenylalanine, tyrosine, tryptophan). One primary mechanism for this thermal stability is the stabilization of tertiary protein structures through π-π stacking interactions between aromatic rings [70]. Concurrently, as extreme environments frequently involve highly thermally agitated water, the aggregation of aromatic rings effectively reduces water penetration within proteins, acting as a "waterproofing (anti-permeation)" mechanism that safeguards biomolecular stability [71]. These phenomena indicate that modern life retains the strategy of protecting and stabilizing structures through hydrophobic stacking of aromatic molecules, a mechanism employed by primordial life under harsh conditions.

The Murchison Meteorite Contains Abundant PAHs, Though these are not the Sole Source of π-π Stacking and Hydrophobic Effects

Beyond PAHs, other molecular types can form analogous structures via π-π stacking and hydrophobic interactions. Nevertheless, PAHs do possess certain distinctive advantages.

Universality of π-π Stacking and Hydrophobic Effects

π-π stacking primarily occurs between molecules possessing aromatic structures (planar conjugated ring systems), such as interactions between nucleic acid bases (adenine, thymine, cytosine, guanine) that stabilize DNA and RNA structures. Aromatic amino acids (e.g., phenylalanine, tyrosine, tryptophan) frequently feature in protein folding [72]. Porphyrin molecules, such as haem and chlorophyll, also exhibit strong π-π interactions within their internal aromatic ring structures. Hydrophobic effects are more widespread, manifesting in any molecule possessing significant hydrophobic regions. Examples include: - Lipid bilayer membranes formed by fatty acids and phospholipids - Non-polar organic molecules such as alkanes and alkenes aggregating into droplets or vesicular structures.

Distinctive Characteristics of PAH Molecules

Compared to the molecules mentioned above, PAHs are distinguished by their high aromaticity and planar structure.

This configuration facilitates close and efficient π-π stacking, allowing them to form stable supramolecular structures more readily. Chemical stability and cosmic abundance: PAHs exhibit high stability, resisting degradation under cosmic conditions such as ultraviolet radiation and cosmic rays. Consequently, they are widely distributed throughout the cosmos, providing an abundant source of prebiotic molecules. Structural diversity and functionalization potential: PAHs possess extensive structural variability. Through oxidation or substituent modification, they can acquire amphiphilic properties, facilitating the formation of stable membrane-like structures in aqueous environments.

Murchison Meteorite and PAHs

The Murchison Meteorite stands as a pivotal sample for studying prebiotic organic chemistry, confirmed to contain abundant PAH molecules. Over several hundred distinct PAH structures have been detected [59]. PAHs within the Murchison Meteorite exhibit not only rich diversity but also multiple forms of substitution and oxidation modifications. PAHs in the Murchison Meteorite are believed to have existed since the formation of the solar system, highlighting their significance in prebiotic organic chemistry.

Although other aromatic molecules may exhibit similar π-π stacking and hydrophobic effects, PAHs stand as unique candidates for early life membrane materials due to their cosmic ubiquity, stability, structural diversity, and abundant experimental and meteorite evidence. The Murchison meteorite's substantial PAH content further supports this perspective, conferring PAHs with significant standing in primordial life origin research [73].

The Close Association of PAHs with Primitive Life in Protoplanetary Discs

PAHs share structural similarities with modern aromatic amino acids and nucleic acid bases, exhibiting π-π stacking and hydrophobic effects. During the origin of primitive life, this interaction may have formed the basis for non-biological membranes or primary aggregates. Modern archaea and thermophilic bacteria retain this characteristic, enhancing thermal stability and water resistance by stacking aromatic amino acids. It demonstrates continuity and conservation in the evolution from primordial to contemporary life forms [74]. In essence, the aromatic molecular stacking effect—from PAHs to modern organisms—represents a crucial continuity strategy spanning abiotic chemical environments to modern life systems, embodying life's evolutionary inheritance of environmental stability and protective mechanisms.

Graphene Generated in Protoplanetary Discs Facilitates the Progression from Prebiotic Chemistry Towards Complex Organic Molecules

Graphene constitutes a two-dimensional crystalline structure formed by a single layer of carbon atoms, essentially representing an idealized, infinitely extended aromatic carbon network. In protoplanetary discs and actual interstellar environments, polycyclic aromatic hydrocarbons (PAHs) are more frequently observed. These can be regarded as molecular incarnations of small graphene fragments [75]. Both experiments and observations indicate that PAHs can survive to some extent within the sparse, low-density, ultraviolet-radiation-dominated interstellar medium (ISM). However, they are subject to degradation by ultraviolet photons and cosmic rays. Theoretical simulations indicate that graphene flakes exhibit enhanced stability under ultraviolet and X-ray irradiation when sufficiently large (>100 carbon atoms) [76]. Thus, graphene-like nanocarbon materials remain relatively stable as protoplanetary discs cool; they can persist for periods within cold, dark interstellar clouds or certain regions, though they cannot withstand prolonged degradation from all radiative and impact environments [77]. Multilayer graphene resists cosmic rays, providing a stable microenvironment for internal molecular reactions.

Adaptability to Extreme Conditions

Graphene exhibits both high-temperature and low-temperature resistance while maintaining its prebiotic catalytic properties and stability for biomolecules. Cryogenic catalysis: Graphene retains its ability to adsorb molecules and catalyze reactions at cryogenic temperatures (~77 K), such as those occurring on interstellar ice crystal surfaces.

Processing or growth of graphene in protoplanetary discs: Within protoplanetary discs, graphene may form through the transformation of polycyclic aromatic hydrocarbons (PAHs), providing ubiquitous templates for prebiotic chemistry. Pre-existing interstellar medium (ISM) dust (containing PAHs, carbon clusters, etc.) aggregates into larger solids and undergoes processes such as thermal treatment and shock melting. These environments may also facilitate the formation or reconfiguration of small graphene-like structures under localized high temperatures, such as during the annealing of carbon-rich parent materials. Thermochemical processes in protoplanetary discs: Carbon clusters (e.g., C_2H_2, PAHs) in inner disc regions (>300 K) can undergo thermopolymerization to form graphene precursors [78]. Laboratory simulations: Methane (CH_4) can generate graphene within high-temperature plasma (mimicking protoplanetary disc conditions). Photochemical synthesis: Ultraviolet radiation at the disc surface drives PAH cross-linking. Observational evidence: Infrared spectra of certain young stellar discs (e.g., HD 97048) reveal broad-spectrum carbon dust features potentially containing graphene fragments [79]. Graphitized carbon, found in meteorites (e.g., the carbonaceous fraction of the Murchison meteorite), exhibits partial graphite-like layered structures, which are thought to relate to thermal processing within protoplanetary discs. In summary, protoplanetary discs can reshape, grow, or consolidate these graphene-like materials through thermal and chemical processes.

High-Temperature Resistance of Graphene

Graphene ranks among the most thermally stable materials known, theoretically remaining stable in inert atmospheres beyond ~2500 °C (with experimentally observed decomposition occurring around 3000K) [80]. The high temperatures generated in protoplanetary disc environments do not readily disrupt graphene's structure, allowing it to maintain surface integrity and catalytic functionality. It implies it retains catalytic or templating capabilities during high-temperature dehydration condensation reactions (e.g., amino acid peptide formation, nucleotide polymerization).

Cryogenic Stability and Durability of Graphene

Even under extreme cryogenic conditions (e.g., 10 K) within cosmic backgrounds, molecular clouds, or ice-encased protoplanets, graphene maintains its structural integrity. Its π-π electron system remains stable without deconstruction upon cooli [81]. Adsorption experiments and simulations suggest that graphene surfaces can adsorb and arrange molecules, such as amino acids, nucleobases, and sugars, at low temperatures without compromising their flatness or electronic properties. It implies it can maintain adsorption and protective capabilities for organic matter in ice-coated or space condensation environments.

Radiation Tolerance of Graphene

Multilayer graphene can withstand cosmic rays, providing a stable microenvironment for internal molecular reactions. Graphene's protective role for biomolecules: Graphene layers function as a "carbon shield" to shield adsorbed molecules from ultraviolet radiation, ionizing radiation, and other hazard [82]. Particularly in environments such as meteorites, space dust, and protoplanetary discs, graphene encapsulation can slow the degradation of organic molecules. It resembles a "prebiotic protective shell" function, holding significant importance for stabilizing and extending the lifespan of organic compounds.

Prebiotic Chemical Catalysis (Template/Catalysis)

Through its π-π stacking and hydrophobic interactions, graphene can promote the ordered arrangement of organic small molecules (such as amino acids and nucleotides), enhancing local reaction efficiency [79]. Both simulations and experiments indicate that it can reduce the activation energy of polymerization reactions, particularly in protoplanetary disc environments. Defective or doped graphene (such as graphene oxide) can also provide acid-base catalytic sites [84].

In the absence of modern enzymes, how might amino acids polymerize into peptide chains or nucleotides condense into RNA on the primordial Earth or in the cosmos? Graphene (or PAH/carbonaceous materials) has been proposed in recent studies as a potential catalytic surface, involving two key aspects: templating effects and dehydration condensation. These are explained separately below:

Potential of Graphene as a Template to Promote Polymerization

Surface Templating Effect

Graphene, being a highly planar, hydrophobic, two-dimensional material with conjugated π electrons, can adsorb aromatic-containing organic small molecules via π-π stacking. Examples include tyrosine and phenylalanine, which bear benzene rings, as well as purine/pyrimidine bases. Concurrently, oxygen-containing edge functional groups (e.g., carboxyl, hydroxyl) can form hydrogen bonds with amino acid NH_2 or COOH groups, enabling directed molecular alignment and facilitating peptide bond formation. Experimental evidence: Laboratory simulations demonstrate that graphene oxide catalyzes the condensation of glycine into dipeptides under mild conditions [85]. It orders adsorption arrangements that enhance local reactant concentration, reduce diffusion freedom, and provide steric proximity for amino acid or nucleotide condensation, potentially lowering polymerization activation energy. Similar surface templating effects have been proposed for clay and metal sulphide surfaces, but graphene or carbonaceous surfaces are more prevalent in carbon-rich dust or meteorite environments.

Graphene Promotes Sequence Specificity

Graphene's surface energy selectively adsorbs different amino acids or bases, forming non-uniform adsorption patterns through differential adsorption energies that may favour the preferential connection of specific residues. It provides a theoretical basis for the formation of particular sequence peptides or oligonucleotides.

Mechanism of Graphene Facilitating Dehydration Condensation (Reverse Hydration Reaction)

The synthesis of major biomolecules requires the removal of water molecules (condensation reactions), yet this is highly unfavourable in aqueous environments. Graphene or PAHs may assist through two mechanisms: a. Hydrophobic environment promotes dehydration: The strongly hydrophobic properties of graphene surfaces repel water molecules, aiding the aggregation of amino acids or nucleotides outside the aqueous microenvironment. It locally reduces water activity, promoting the reverse hydrolysis of condensation reactions. That is, the hydrophobic microenvironment—specifically the hydrophobic regions between graphene layers—can repel water molecules, lowering the water activity required for peptide bond formation (analogous to the dehydration action in the active sites of biological enzymes). b. Surface defect sites: Unbonded bonds or oxygen-containing groups at graphene edges may directly participate in proton transfer, thereby assisting in dehydration and condensation.

Role of Graphene in Nucleotide Condensation to form RNA Template for Phosphodiester bond Formation

- **Electrostatic interactions:** Negatively charged phosphate groups (PO_4^{3-}) may bind to positively charged regions on the oxidized graphene surface (e.g., protonated -OH groups), enabling directional alignment of nucleotides ( ) and facilitating 5'-3' phosphodiester bond formation.
- **Base stacking:** The planar structure of nucleotide bases (e.g., purines, pyrimidines) can adsorb onto the graphene surface via π-π stacking, increasing local concentration and promoting condensation.

Dehydration and Stability

- **Water exclusion:** Hydrophobic regions of graphene may reduce reverse hydrolysis reactions, protecting newly formed RNA chains.
- **UV shielding:** Graphene's high absorption of short-wave radiation (e.g., UV-C) may shield fragile RNA precursor molecules from photodegradation.

Experimental and Theoretical Support

- **Laboratory Studies:** Graphene oxide has been demonstrated to catalyze the condensation of nucleotides (e.g., AMP) into short RNA chains (~4–6-mer oligomers) under simulated primordial Earth conditions.
- **Quantum Computing Simulations:** Modelling indicates graphene surfaces can reduce the activation energy for phosphodiester bond formation (by approximately 10–15%).

Graphene Energy Transfer and Catalysis, Photothermal Effect

Graphene generates hot electrons under UV/visible light, potentially activating amino acid carboxyl groups (—COOH) or amino groups (—NH_2), thereby lowering reaction energy barriers [86]. Metal Impurity Assistance: If graphene contains trace metals such as Fe or Ni (derived from interstellar dust), these may further catalyze redox reactions (e.g., thiol-disulphide bond exchange, promoting the formation of complex peptide chains).

Carbon Nanotubes in Protoplanetary Discs

The curling of graphene can form carbon nanotubes (CNTs), which possess both similarities and unique advantages compared to graphene in prebiotic chemistry (such as amino acid polymerization or nucleotide condensation).

Mechanism of Graphene Curling to Form Carbon Nanotubes

Graphene constitutes a two-dimensional plane of carbon atoms. When curled along one dimension to form a closed cylinder, it transforms into a carbon nanotube (CNT); if curled into a spherical closed structure, it forms a fullerene (e.g., C_{60}). Under high-temperature or strongly excited conditions (such as intense ultraviolet irradiation in protoplanetary discs), graphitized polycyclic aromatic hydrocarbons (PAHs) or graphene fragments can spontaneously curl via surface tension and chemical rearrangement, forming nanotube-like or fullerene-like structures. In cosmic environments or protoplanetary discs, such curling may occur under conditions of localized high temperatures coupled with extremely rapid cooling rates—traces of carbon nanotubes and fullerenes have been detected in meteorites, indicating that CNTs can indeed form naturally. Catalyst-assisted: Metal nanoparticles (e.g., Fe, Ni) within protoplanetary discs may serve as nucleation sites, guiding graphene to curl into tubes (similar to the mechanism for synthesizing CNTs via chemical vapour deposition).

Role of Carbon Nanotubes in Amino Acid Polymerization and RNA Condensation

The potential of carbon nanotubes (CNTs) as templates for life's origins has gained support from multiple experiments and simulations in recent years, primarily through the following mechanisms [87]:

Adsorption and Ordered Arrangement (Template Effect)

The CNT surface exhibits strong π-π interaction capabilities, enabling adsorption of amino acids containing aromatic groups (e.g., phenylalanine, tyrosine) and the base portions of nucleotides (particularly purines) [88,89]. Simulations indicate that these molecules arrange axially along the CNT surface in linear chains, reducing intermolecular degrees of freedom and diffusion while substantially enhancing the probability of polymerization. The hollow CNT structure confines amino acids within nanoscale spaces, increasing collision frequency.

Hydrophobic Environment Facilitates Dehydration Condensation

Like graphene, the CNT surface is highly hydrophobic, confining adsorbed molecules within a microenvironment of low water activity conducive to dehydration condensation. Concurrently, the hydrophobic graphene walls of CNTs repel water, reducing the water activity required for peptide bond or phosphodiester bond formation (analogous to the hydrophobic pockets of enzymes).

Catalytic Energy Transfer and Stabilization

CNT edges (containing defective edge carbon) or doped CNTs (e.g., N-doped) provide acid/base sites that further promote peptide bond or phosphodiester bond formation. Photothermal Conversion: CNTs generate localized hot spots under UV/visible light, potentially activating molecular vibrations and lowering reaction activation energy. Protective Function: The enclosed structure of CNTs shields internal RNA precursors from interstellar ultraviolet radiation damage.

Comparison of Carbon Nanotubes and Graphene

Compared to graphene planes, CNTs provide curved surfaces that form a "nanotube lumen" microenvironment. It allows molecules to adsorb not only on the outer wall but also potentially enter the inner wall space, facilitating further molecular concentration. The curvature also influences π-π stacking energy, promoting more regular molecular orientation. It is particularly crucial when forming sequence-specific oligonucleotides or oligopeptides. CNTs provide a more three-dimensional, enclosed or semi-enclosed templating environment than graphene [90].

Carbon Nanotubes (CNTs) in Interstellar Environments

Protoplanetary Discs: High temperatures and metallic catalysts favour CNT formation. Radiation Resistance: CNTs' closed structure offers superior UV/cosmic ray resistance compared to graphene (experiments indicate higher proton irradiation damage thresholds for CNTs). Chemical Inertness: Whilst susceptible to oxidative cleavage by hydroxyl radicals, CNTs can persist long-term after protoplanetary discs cool. The surface or internal microenvironment of CNTs may simultaneously promote the formation of amino acid peptides, nucleotide pairing/stacking, as well as condensation and dehydration reactions [91]. Although CNTs have not yet been detected in protoplanetary discs or meteorites, as an intermediate product between graphene and fullerenes already found in meteorites, their future confirmation could provide a key mechanism explaining the abiotic synthesis of biomolecules under extreme conditions [79].

Fullerenes in Protoplanetary Discs

Principle of Top-down Conversion of Graphene to Fullerenes in Protoplanetary Discs

Within protoplanetary discs, micrometre- or nanometre-scale graphitized carbon flakes (i.e., small graphene sheets) readily undergo edge carbon bond cleavage and carbon framework rearrangements when exposed to intense ultraviolet radiation, shockwaves, or high-temperature annealing [92]. Simulations and experiments indicate that when graphene-like PAHs undergo intense photolysis, edge carbon atoms lose hydrogen or undergo fragmentation [76]. The residual carbon fragments naturally curl due to surface tension, forming closed spherical shells and spontaneously transforming into fullerenes (such as C_{60} or C_{70}). This process is termed top-down synthesis, meaning large graphene/PAH structures first form before photochemical or thermochemical erosion converts them into fullerenes, rather than direct one-step synthesis from gaseous carbon atoms (which is bottom-up) [93]. Within protoplanetary discs, regions close to the star (high-temperature zones of several hundred to several thousand K) and areas experiencing transient flares provide ideal environments for converting graphene-like materials into fullerene [94]. In the laboratory, fullerenes can form spontaneously through the condensation of carbon vapour from graphite arc evaporation. In the cosmos, intense ultraviolet radiation and shock environments within planetary nebulae can drive analogous processes. The presence of C_{60} and C_{70} has been confirmed observationally in nebulae such as Tc1 [95]. Thus, the curling of graphene into fullerenes is indeed a plausible transformation process that occurs in natural environments [96]. In 2010, scientists at the University of Western Ontario, Canada, discovered evidence of C_{60} in cosmic nebulae over 6,500 light-years away. They detected C_{60}'s characteristic spectral signature using the Spitzer Space Telescope [92].

Potential Templating or Catalytic Roles of Fullerenes in Amino Acid Peptide Formation and RNA Condensation

Following fullerene formation, their potential roles in primordial chemistry regarding templating effects and dehydration catalysis differ from those of graphene or CNTs:

Limited Adsorption Capacity

The fullerene surface is closed and highly symmetrical (C_{60} being a perfect sphere), lacking the extensive planar surfaces or hollow spaces found in graphene or CNTs. It can transiently adsorb aromatic groups (e.g., the benzene ring in amino acids and purine bases) via π-π interactions, but does not provide a template space for large-scale, ordered arrangement.

Limited Dehydration Promotion

The hydrophobic nature of fullerene surfaces facilitates local repulsion of water molecules, theoretically providing a microenvironment conducive to dehydration condensation. However, unlike two-dimensional graphene or one-dimensional CNTs, it cannot efficiently arrange and immobilize reactants.

Lack of Catalytic Activity

The absence of edge active sites, coupled with the absence of Lewis acid/base centres found in clays or metal sulphides, precludes active catalysis of condensation chemistry.

Fullerene Rosette Hypothesis

Fullerenes (such as C60 or C70) may have played a role in promoting the evolution of biomolecules within protoplanetary discs, particularly involving the specialized structure known as the fullerene rosette. Fullerenes constitute approximately 1% of the total carbon content in protoplanetary discs. Even in modern society, where fullerenes are generated from meteorite and coal consumption on Earth, their abundance is only one part per hundred million to one part per billion of that found in protoplanetary discs. Therefore, when discussing the role of fullerenes in the origin of life, their abundance also serves as excellent corroborating evidence for life originating in protoplanetary discs.

Significance of Fullerene Rosettes

Fullerene Rosettes (Fullerene-Rosetta, or “Fullerene Rosette Structures”) refer to the possibility that fullerene molecules (particularly C60 and C70), with their unique hollow cage-like structures, may have served as support frameworks or catalytic platforms for the initial polymerization of nucleotides (RNA or similar molecules). This structure provided a stable environment for polymerization, facilitating chain extension and polymerization of primordial nucleotides, thereby promoting the complexity of biomolecules.

Parallel Lines of Evolution May Challenge RNA- and DNA-First Theories

Traditionally, mainstream theories of life’s origin emphasize RNA or DNA as the primary “genetic material” or information carrier (e.g., the “RNA World Hypothesis”). The fullerene rosette hypothesis proposes an alternative evolutionary pathway, suggesting multiple parallel evolutionary routes existed in life’s early stages. Fullerene molecules may have supported an independent evolutionary branch, challenging the primacy of RNA or DNA. It reflects a broader perspective that life’s evolution may have been diverse rather than singular from its inception.

Tri-Nucleotide Chains Initially Attached to Fullerene C60 or C70

This hypothesis posits explicitly that the earliest nucleotide chains may have been anchored to the surface of fullerenes. These trinucleotide chains (sequences of three nucleotides) may have constituted the most stable coding units in the earliest stages of life, subsequently forming the basis of the genetic code (triplet codon) [97]. The genetic code of modern organisms is indeed based on the triplet nucleotide (codon) as its fundamental unit of coding. Precisely for this reason, the fullerene-platform-supported “triptan origin” theory may offer a novel explanation for the origin of the “triplet code [98].”

Fullerene Layers and Early Amino Acids

Furthermore, this theory suggests that the structural characteristics of fullerenes may also have determined the early sequence of specific amino acid emergence. It particularly supports the notion that the ten essential amino acids likely constituted the earliest amino acids in life [99]. These amino acids are thought to have initially interacted more stably with fullerene molecules, thereby being favourably selected during the early origins of life [100].

Three Hypotheses Grounded in the Protoplanetary Disc

Through the preceding discussion, we observe that fullerene structures support the following hypotheses: the fullerene provides a platform for the initial formation and stabilisation of biomolecules; the codon length hypothesis posits that the three-nucleotide length may stem from structural constraints of the fullerene platform; and the hypothesis of the early emergence of essential amino acids suggests that amino acids interacting more stably with fullerene may have appeared earlier and integrated into life systems. Our physical investigations into the stable platform for early molecules, the structural constraints on three-nucleotide length, and the early emergence of essential amino acids are all grounded in the context of the protoplanetary disc.

Fullerene (C_{60}) as a Potential Energy-Harvesting, Photocatalytic, or Electron-Transfer Molecule in the Protoplanetary Disk Environment

The most distinctive potential of fullerenes in the origins of life lies in their function as energy-harvesting, photocatalytic, or electron-transfer molecules, which may have helped drive prebiotic chemistry. Within protoplanetary discs, prebiotic chemistry required energy to catalyze reactions that transformed simple molecules into complex ones. Life forms such as archaea (electrophagous bacteria) also require energy, including light, to convert electrons into nutrients they can utilize.

Fullerene’s Energy Harvesting Capability

As natural “photon trappers”, fullerenes C_{60} and C_{70} possess highly symmetrical closed π-conjugated systems capable of highly efficient absorption of photons spanning the ultraviolet to visible spectrum (200–600 nm). Upon excitation by photons, C_{60} enters a long-lived excited triplet state, meaning it can store absorbed light energy and has time to transfer this energy to nearby molecules [101]. In prebiotic environments, the capture of light energy and the long-lived excited state may have facilitated local chemical reactions, such as energy-dense condensation or reduction processes.

Photocatalysis and Electron Transfer

Excited-state fullerenes are potent oxidizing/reducing agents. Excited-state C_{60} can react with neighbouring small molecules via single-electron transfer, exhibiting characteristics of both a strong oxidant and a reducing agent. In prebiotic environments, where reducing organic small molecules (such as simple aldehydes, ketones, or carboxylic acids) are present, the excited fullerene state can transfer electrons to these molecules, triggering the formation of carbon-carbon or carbon-nitrogen bonds. Similarly, in oxygen-rich environments, C_{60} can generate reactive oxygen species (e.g., singlet oxygen), which, under suitable conditions, may catalyze further chemical transformations of molecules [102].

Energy Coupling to Organic Reactions

Potential Links to Prebiotic Synthesis. Kroto (discoverer of C_{60}) proposed that if fullerenes existed in primordial environments, they could function as natural photocatalysts. Under intense ultraviolet radiation, they may transfer energy to simple organic molecules, driving bond formations that are difficult to achieve spontaneously [103]. It differs from the conventional view (where clay and metal sulphides provide catalytic surfaces): fullerenes act as non-contact photochemical energy mediators, capable of initiating chemical reactions without close adsorption.

Ultraviolet Shielding

While protecting molecules and regulating energy, fullerenes exhibit strong ultraviolet absorption and may function as a localized "UV protective layer": shielding key organic molecules from excessive ultraviolet damage; simultaneously regulating partial ultraviolet energy to drive chemical reactions requiring energy input [104].

In summary, fullerenes play a significant role in the origin of life within protoplanetary discs. Fullerenes function not as clay-like templates, but as molecular machines for collecting and converting light energy; they can transform solar energy into chemical energy usable for synthetic reactions within intense UV environments. It may represent a crucial mechanism for prebiotic molecular energy coupling in the early, UV-rich Earth or protoplanetary discs. Subsequent sections will further explore how fullerenes, combined with F-S worlds, facilitate energy conversion and provide essential nutrients for bacterial growth.

Comparison of Prebiotic Chemical Environments on Earth and in Protoplanetary Discs

Exploring the chemical foundations of life's origin cannot be divorced from the physical environment upon which it depended. Although both the protoplanetary disc and early Earth possessed organic chemical potential during these critical phases, their markedly different energy inputs, elemental abundances, and catalytic environments dictated unequal roles in synthesizing precursors to life. Comparing these environments helps clarify which key chemical steps may have been partially completed off-Earth or were fundamentally impossible on Earth, thereby identifying the most probable sources of "pre-processed molecules" that facilitated the emergence of life.

The Early Earth Environment: Mild and Stable

Following its formation, the early Earth underwent rapid and violent planetary differentiation, coinciding with the Heavy Bombardment phase. However, as the mantle cooled and the crust formed, the surface environment stabilised relatively, exhibiting the following characteristics: Atmospheric Formation and Magnetic Shielding: A primordial atmosphere began to accumulate, while the geomagnetic field generated by the forming core effectively shielded against solar wind and cosmic rays; Reduced Radiation Levels: Compared to interstellar space and the protoplanetary disc, surface radiation levels were lower, with UV/X-rays attenuated by the atmosphere; Limited Metal Abundance: Transition metals (e.g., Fe, Ni, Co) were predominantly concentrated in the core, with relatively low and unevenly distributed levels in the crust; Surface Water Bodies and Sedimentary Systems: A stable liquid water environment facilitated dissolution reactions, molecular diffusion, and sedimentation, though reaction activity remained low [105]. Consequently, whilst Earth may be conducive to sustaining reactions and stabilizing polymers, it may lack the initial conditions for high-energy excitation, complex synthesis, and the initiation of catalytic networks.

Protoplanetary Disk Environment: Energy-Rich, Metal-Rich, Catalyst-Rich

By contrast, protoplanetary discs offer significant chemical advantages: High radiation flux: X-rays and UV radiation from young stars (e.g., T Tauri stars) are exceptionally intense, with cosmic rays exhibiting high penetrating power; Diverse energy sources: Beyond radiation, these include 26Al, 60Fe; Abundant transition metals: Fe, Ni, Co and other transition metals injected by AGB stars and supernova explosions are widely distributed within the disc; Abundant mineral catalysts: Dust particles, hydrated silicates and metal oxides provide surfaces and structural templates for chemical reactions; Abundant formation of organic precursors: numerous biosynthetic precursor molecules including formaldehyde, HCN, methylamine, and PAHs have been observed [106]. The atomic-molecular synthesis activity during this phase far exceeds that on Earth, sufficient to achieve substantial preliminary accumulation of amino acids, nucleotides, fatty acids, and sugar precursors within a million-year timescale.

Interplanetary Transport and Preservation of "Preformed Molecules" or Proto-Life

Complex organic compounds within protoplanetary discs may have formed life in situ and subsequently 'delivered' it to Earth's surface via the following mechanisms: Organic-rich asteroids and comets— such as carbonaceous chondrites, Oort Cloud objects, and Kuiper Belt ices; Low-velocity impacts and high-pressure transients: Under specific impact conditions, organic compounds may evade high-temperature destruction and become embedded within the crustal surface layer; Meteorites and interstellar dust: Such as the dozens of α-amino acids and nucleobase-like compounds detected in the Murchison meteorite; Fullerene and PAH carriers: Spherical carbon cages encapsulating organic compounds or amino acids may serve as protective shells within space. This evidence suggests that the early Earth may not have been an "isolated chemical system," but instead underwent an environmental adaptation process, receiving "pre-processed molecules" or primordial life cells from the protoplanetary disc [59,107-110].

The protoplanetary disc environment provided catalytic and energetic conditions far exceeding those on Earth for organic synthesis. At the same time, Earth served as a mild and stable "polymerization field" to complete the subsequent integration of life's adaptability to the terrestrial environment after its birth in the protoplanetary disc [111]. Suppose the chemical evolution pathway of life is viewed as a chain. In that case, the protoplanetary disc constitutes the "head segment" and Earth the "tail segment", with the link between them furnished by "chemical and life couriers" such as meteorites, comets, and interstellar dust. This perspective not only broadens our spatiotemporal understanding of life's origins but also provides theoretical support for the protoplanetary disc's mechanism for disseminating life.

The foregoing elucidates the most critical issue within the protoplanetary disc theory of life's origin: the environmental question. That is to say, analysis from multiple dimensions indicates the protoplanetary disc was more conducive to the emergence of Earth-based life. If the birth of life on Earth were deemed improbable, then based on the above analysis, the protoplanetary disc represents the optimal starting point for Earth's life. Environmental analysis of the protoplanetary disc from every angle strongly favours the emergence of life, providing an exceptionally favourable incubator for its birth.

Why is HCN crucial for the transition from chemistry to biology?

Radio astronomy has unequivocally detected HCN in interstellar molecular clouds and cometary comae [112, 113]. Pre-planetary discs also contain significant HCN. Its extreme toxicity and high reactivity are precisely why it can construct complex molecules [114].

HCN's Chemical Reactivity is Key to its Role as the "Source of Life"

The Potent Cyano Group (-C≡N)

This group exhibits strong electron-withdrawing properties, rendering the carbon atom it bonds to electron-deficient (electrophilic), making it highly susceptible to attack by nucleophiles (such as ammonia, water, or other HCN molecules). It acts like a "chemical magnet", readily initiating a cascade of chain reactions.

Polymerization Reactions

HCN molecules can undergo polymerization, forming complex networks and cyclic structures. Upon hydrolysis, these polymers yield core building blocks of life. HCN tetramer: Four HCN molecules polymerize to form aminopyrimidine, a direct precursor to adenine (A, a DNA/RNA base) [115]. HCN oligomers: Hydrolysis of HCN polymers yields precursors for various amino acids (e.g., glycine, aspartic acid), purines (adenine, guanine), and pyrimidine bases [116].

The "Common Origin" Chemistry of RNA, Proteins, and Lipids

The "cyanosulfidic chemistry" proposed by the Sutherland group demonstrates that, starting from HCN and its derivatives, the key precursors for the three major subsystems—ribonucleotides, amino acids, and lipid precursors—can be derived from the same chemical pathway under mild conditions such as sulphite/light reduction. It explains how RNA, proteins, and lipids can emerge in parallel without awaiting the formation of each other [117].

Classic Milestones

As early as 1960–61, Oro demonstrated the non-biological synthesis of adenine from HCN (→) via intermediates such as DAMN, establishing prototype evidence that "purines can be generated through the HCN pathway" [118].

HCN Itself is Volatile/Oxidatively Labile, yet can be "Mineralized into Reservoirs" Within Alkaline Brines/Minerals (e.g., as ferrocyanides, cyanates, etc.), subsequently "released" during evaporation–concentration–photoreduction or thermal events to continue downstream synthesis. It precisely explains why many prebiotic experiments employ "HCN and its derivatives" rather than free HCN alone. For instance, liquid chromatography-high-resolution Orbitrap mass spectrometry analysis of a series of primitive meteorites (carbonaceous chondrites), particularly Lewis Cliff 85311, revealed releasable cyanide primarily present as [FeII(CN)5(CO)]3- and [FeII(CN)4(CO)]2-. Crucially, [FeII(CN)5(CO)]3- and [FeII(CN)4(CO)]2- exhibit dual characteristics: (a) they are "classical" organometallic compounds with ligand spheres composed of CO and CN-; (b) both organometallic compounds resemble the active sites of primordial cellular hydrogenases [119].

In summary, HCN is not an "energy substrate" (it inhibits cytochrome oxidase). Still, it constitutes a building-block library: capable of introducing "one-carbon" units in a high-energy state, extending into key modules such as purines/pyrimidines, amino acids, and lipid precursors. HCN serves as the common chemical ancestor for numerous critical structures within modern life's "information molecules" (nucleic acids) and "functional molecules" (proteins).

Transition from Prebiotic Chemistry to Biochemical Metabolism

Prebiotic Stage

At this stage, there is no life, no enzymes, and no metabolism. Reactions depend on physical and chemical conditions (concentration, temperature, pH, mineral catalysis, ultraviolet irradiation, etc.). HCN is the undisputed "star raw material" during this phase. Its reactions are spontaneous and non-enzymatically catalyzed.

Biotic Metabolic Stage

Once life emerged, it evolved highly refined, enzyme-catalyzed metabolic pathways. These pathways discarded primitive, inefficient, and destructive chemical reactions in favour of efficiency and specificity.

- **The Toxicity of HCN:** Hydrocyanic acid (HCN) strongly inhibits cytochrome c oxidase, blocking aerobic respiration, and is therefore highly toxic to modern life.
- **Evolution of Metabolism:** Modern organisms synthesize amino acids and nucleotides without requiring hazardous oligomerization processes that start from HCN. They possess safer, more efficient enzymatic pathways (e.g., utilizing intermediates such as aspartic acid in the synthesis of purines).
- **Resistance and Reuse:** Some microorganisms later evolved the ability to degrade HCN (as a nitrogen or carbon source) or produce it as a defence mechanism (as in particular Pseudomonas species you mentioned) [120]. It represents a subsequent evolutionary adaptation, exploiting an existing environmental toxin rather than indicating its origin [121].

Thus, HCN's prebiotic significance lies in providing a non-biological pathway for generating reliable chemical routes to life's most fundamental building blocks. It explains how life's bricks were 'fired' through purely chemical processes before enzymes emerged. Its absence from modern mainstream metabolism precisely demonstrates life's evolution—from dependence on chaotic chemical environments to mastery of highly ordered intracellular metabolism [122]. As a "component library," HCN interlinks "one-carbon chemistry," lowering the "assembly threshold" from small molecules to nucleosides, amino acids, and lipid precursors. It is precisely why it is deemed "of profound prebiotic significance."

The Central Role of Protoplanetary Disks in Prebiotic Chemical Evolution

As a natural by-product of star formation, the protoplanetary disc is not merely a site for planetary material accumulation but also exhibits a complex, energy-rich, and chemically active environment. It provides a series of favourable conditions for the synthesis and accumulation of precursors to life. From radiation excitation to radionuclide decay, and from transition metal catalysis to synergistic reactions between polycyclic aromatic hydrocarbons and dust particles, the protoplanetary disc constructs a complex chemical reaction network driven by multiple energy sources, involving numerous components, and featuring various parallel pathways [123,124]. This network not only possesses the capacity to generate fundamental organic compounds, such as amino acids, nucleotides, and fatty acids, but may also provide structural templates and energy support for higher-level structures, including self-assembled membranes, primordial enzyme active sites, and even primordial metabolic networks [39,125].

Particularly, localized heating by long- and short-lived radionuclides (such as ^{26}Al, ^{60}Fe, ^{238}U, ^{232}Th, and ^{40}K), high-flux irradiation from stellar UV/X-rays, and the interactions between mineral surface catalytic reactions and self-assembly capabilities, rendered the protoplanetary disc environment vastly superior to the early Earth's surface in terms of chemical evolution efficiency and complexity. Earth may not have started from scratch, but rather integrated these "prefabricated prebiotic chemical modules, including even cells," within its relatively temperate environment, thereby driving the adaptation and evolution of life.

Looking ahead, the connection between protoplanetary discs and prebiotic chemistry may be further tested and deepened through: Astronomical observations: High-resolution imaging of organic molecules, metallic elements, and temperature structures within young stellar discs using infrared and millimetre-wave telescopes (e.g., JWST, ALMA): Acquiring more representative organic-rich samples through ground-based and return missions (e.g., OSIRIS-REx, Hayabusa2); Interstellar and Planetary Simulations: Reconstructing protoplanetary disc conditions—temperature, radiation, and mineralogy—in laboratories to test the feasibility of key synthetic reactions; In situ detection: Future space missions to comet-like bodies, hot protostellar discs, or the comet nucleus–nebula transition zone (such as ESA's Comet Interceptor) will reveal their primordial organic chemistry [107,109,126-128].

These interdisciplinary studies will help answer a grander question: "Is Earth-like life the norm in the cosmos?" [129]. Suppose the chemical mechanisms within protoplanetary discs are indeed universally capable of constructing life. In that case, the initial raw materials and pathways required for Earth-like life may not be unique to our planet, but rather universal products of natural evolutionary processes within cosmic nebulae [130]. It not only prompts us to reconsider the 'geocentric view', but also provides theoretical guidance and prioritization for seeking 'biosignatures' beyond our solar system.

The Origin of Food or Initial Organic Molecules within Protoplanetary Discs and Prebiotic Chemical Evolution

The question of life's origin remains one of the most fundamental and complex issues in the natural sciences. Modern research increasingly indicates that life did not emerge as an isolated, post-Earth-formation accident, but may instead be deeply rooted in earlier cosmic chemical evolution. Astrochemistry, as the core discipline studying the evolution of atoms and molecules in the cosmos, offers new perspectives on understanding the origins of life-forming substances. Against this backdrop, the protoplanetary disc—the circumstellar gas and dust disc surrounding stars during their formation—emerges as a crucial transitional stage linking interstellar matter to the chemical potential for life.

The formation of protoplanetary discs begins with nebular collapse, resulting in a flattened structure that conserves angular momentum and undergoes multiple evolutionary stages, from dust aggregation and minor body formation to protoplanetary collisions. Throughout this process, the combined effects of stellar radiation, high-energy particle streams, the decay of short-lived isotopes, and internal heat sources foster highly active chemical reactions within the disc. This environment not only contains the fundamental elements for life—CHNOPS—but also enriches various metallic elements, particularly transition metals, potentially providing potent catalytic support for primordial organic synthesis reactions. Observations and meteorite sample studies indicate that these discs are not only rich in organic molecules (such as formaldehyde, HCN, polycyclic aromatic hydrocarbons PAHs, etc.), but also contain substantial quantities of transition metals (e.g., Fe, Ni, Co) and short-half-life radioactive isotopes (e.g., (26)Al, ^{60}Fe), and long-lived radioactive isotopes (such as potassium-40 (^{40}K), uranium-238 (^{238}U), uranium-235 (^{235}U), and thorium-232 (^{232}Th)). These elements provided catalysis and energy sources for diverse chemical reactions.

However, the precise role of metals—particularly transition metals—in prebiotic chemical reactions remains poorly understood. Can their multivalent nature, coordination behaviour, and electronic structure facilitate key molecular synthesis, energy transfer, and structural selectivity within protoplanetary discs? These questions not only inform our understanding of life's origins but also influence speculations regarding the potential for life on Earth-like planets.

This study aims to systematically investigate the distribution, chemical properties, and catalytic potential of transition metals within protoplanetary discs. By analyzing their potential core role in prebiotic chemical reactions, we explore the origins of initial organic molecules and the evolution of prebiotic chemistry. Integrating meteorite chemical analyses, simulation data, and evolutionary clues from modern biological metal enzymes, we attempt to delineate a continuous pathway from protoplanetary disc metallochemistry to the origin of life within these discs.

Cosmic Origins of Life's Fundamental Elements and the Chemical Habitability of Protoplanetary Discs

The fundamental building blocks of life comprise carbon (C), hydrogen (H), nitrogen (N), oxygen (O), phosphorus (P), and sulphur (S), collectively termed CHNOPS. These elements are extensively present within protoplanetary discs in gaseous, icy, compound, and dust forms [15]. Moreover, transition metals (TM), an indispensable class of elements in life systems, are also abundant in protoplanetary discs, particularly within iron-rich dust and supernova-injected regions. These metals—including iron (Fe), nickel (Ni), and cobalt (Co)—are widely present in meteorites, interstellar dust, and protoplanetary bodies during the early stages of disk formation [131].

The ubiquity and critical role of transition metals in biological systems are well-established: approximately 30% of proteins contain metal-binding structures, and around 40% of enzyme-catalyzed reactions depend on metalloproteins [132]. Within organisms, these metals typically form metal-organic complexes, performing core functions in catalysis, electron transfer, and redox processes, as well as maintaining structural stability [133]. Notably, transition metals from the first period of the periodic table are found in nearly all phyla of life, indicating their widespread utilization during early evolutionary development [134].

More significantly, transition metals possess unique electronic structural flexibility, as they exhibit multiple oxidation states, spin states, and variable ligand geometries, and can undergo reversible electron transfer with σ/π donor or acceptor ligands, thereby participating in complex chemical reactions [135]. This chemical versatility renders them indispensable catalytic agents in prebiotic chemistry, particularly suited to catalyze initial metabolic networks and nucleic acid precursor synthesis reactions under non-enzymatic conditions [136].

Within protoplanetary discs, the CHNOPS elements, transition metals, and alkali metals (such as sodium and potassium) collectively constitute the elemental environment essential for life. Unlike later terrestrial environments, these elements exist in more primordial and reactive forms within protoplanetary discs (e.g., ionic states or bound to highly reactive dust particle surfaces), providing a natural platform for non-equilibrium chemical reactions. Thus, protoplanetary discs serve not only as material sources for prebiotic chemical systems but also as the "chemical cradle" where the earliest life-related chemical evolution likely occurred, constructing the molecular frameworks and reaction pathways essential for life [137].

Consequently, the origin of life was likely not an isolated Earth-specific process, but rather a continuation of the chemical evolution already underway within the protoplanetary disc. This perspective not only supports an understanding of the universality of life's origins but also establishes a cosmic framework for exploring exoplanetary life by providing the material and reaction foundations.

Cosmic Origins of Metallic Elements in Protoplanetary Discs

The chemical composition of protoplanetary discs is not formed in isolation but inherits the "legacy" of stellar nucleosynthesis from millions of years before the Sun's formation. The Sun formed within a heavy-element-rich molecular cloud in the Milky Way, which gradually accumulated the elements essential for life and planetary bodies through successive generations of stellar explosions, wind erosion, and mergers. Current astrophysical and cosmochemical research unanimously indicates that supernova explosions, AGB stellar winds, and binary neutron star mergers are the primary sources of heavy elements in protoplanetary discs, particularly transition metals and rare radioactive nuclides [138].

Type II Supernovae

Massive stars undergo violent supernova explosions at the end of their evolution, releasing the diverse metallic elements formed through nuclear fusion within their cores into the surrounding space [139] . These explosions constitute the primary source of iron-peak elements (Fe-peak elements), including iron (Fe), nickel (Ni), and cobalt (Co). Such explosions also produce short-lived radioactive isotopes (such as ^{26}Al and ^{60}Fe), providing a crucial driving force for thermal energy generation within protoplanetary discs [140].

Asymptotic Giant Branch (AGB) Stellar Winds: Carbon, Nitrogen, and s-Process Metal Injection

During the late stages of their evolution, intermediate-mass stars enter the Asymptotic Giant Branch (AGB) phase, undergoing significant mass loss. Their stellar winds enrich interstellar space with carbon, nitrogen, oxygen, and s-process (slow neutron capture) elements, such as barium (Ba), strontium (Sr), zirconium (Zr), and lanthanum (La) [141]. These particles condense upon cooling to form carbon-rich or oxide dust, serving as a crucial source of organic chemistry within protoplanetary discs and constituting a primary origin for building blocks of organic compounds in protoplanetary discs and carbonaceous chondrites.

Double Neutron star Mergers and R-Process Element Injection

Although rare, binary neutron star mergers are a significant source of r-process (rapid neutron capture) elements, producing heavy metals such as platinum (Pt), gold (Au), and rare-earth elements like neodymium (Nd) and gadolinium (Gd). Although their injection rates are far lower than those from supernova explosions and AGB stellar winds, the metals produced are diverse and possess special functionalities in biochemistry, such as forming the metallic active centres of specific enzymes or serving as electron pathways in catalytic reactions [142].

These nucleosynthetic products accumulated within molecular clouds in diverse forms (atomic, ionic, oxides, sulphides, carbides, etc.) via interstellar dust or gas molecules, subsequently being drawn into the protoplanetary disc during the nebular collapse that formed the Sun [143]. Thermal evolution within the protoplanetary disc and planetary microbody collisions further promoted localized aggregation of these metals or their involvement in catalytic reactions, providing metallic cores for early chemical reaction systems.

As these metallic elements were partially segregated into the Earth's core or redistributed during planetary formation, the metallic abundance in the protoplanetary disc's early stages far exceeded the levels available in the Earth's present-day surface layers. Consequently, numerous critical metal-catalyzed reactions—such as Fischer-Tropsch synthesis, nitrogen fixation, and reductive amination—were likely pre-initiated within the protoplanetary disc, establishing the material and reaction foundations for subsequent biogeochemical evolution.

Fe/Co/Ni Metal Coordination Compounds Facilitate Prebiotic Reactions

Transition metals can form stable coordination compounds with simple small molecules (e.g., CO, NO, HCN, N_2, H_2), serving functions including: Bond activation: Metal centres can "soften" molecular π or σ bonds, facilitating their cleavage or rearrangement; Electron transfer bridges: Acting as Lewis acids or reducing agents to transfer electrons between different molecules; Selective regulation: Metal coordination can direct molecular arrangement, enhancing reaction pathway selectivity. For example:

- Fe^{2++} /Fe^{3+} : Catalyses $CO + H_2 \rightarrow\rightarrow$ (hydrocarbons; Fischer–Tropsch reaction);
- Ni^{2++} activates H_2 with $C\equiv N$, promoting hydrogen cyanide reduction to methylamine or aminonitrile;
- Co^{3+} forms Co–NO complexes with NO, mimicking the function of modern nitric oxide synthases.

Simulation experiments indicate that such metal-small molecule complexes can form on mineral surfaces (e.g., olivine, ferrite) at temperatures ranging from 200 to 400 K, exhibiting higher activity than in metal-free environments [144].

Metal–Organic Complexes as Prototypes of Metalloproteins

In modern organisms, the active sites of numerous core enzyme systems contain metals such as Fe, Ni, or Co, exhibiting evolutionary continuity with primordial complexes. Examples include: iron-sulphur clusters (Fe–S clusters): composed of structures like $[Fe_4S_4]^{2++}$, extensively involved in electron transport chains (e.g., ferredoxin); Hydrogenases ([FeFe] or [NiFe] hydrogenases): catalyse the reversible conversion between protons and hydrogen gas; Nitrogenases: contain complex FeMo or FeV clusters, catalysing the $N_2 \rightarrow NH_3$ reaction; Cobalamin (Vitamin B_{12}): centred on Co^{3++} , participates in methyl transfer and homologous recombination [145,146].

These structures demonstrate that life systems did not invent new chemistry, but rather directly 'inherited' pre-existing metal complex forms from nature. Upon this foundation, functionalized macromolecular platforms (such as proteins and RNA) were constructed to encapsulate and regulate these complexes.

From Nebula to Life: The Continuity of Metal Complexes

Metal–small molecule or metal–PAH complexes formed within protoplanetary discs not only provided primordial electron transfer and bond activation mechanisms but may also have been captured by vesicles, membrane-like structures, or RNA fragments, evolving into "primordial catalytic nuclei". For instance, studies indicate that: Fe–S clusters may self-assemble directly from Fe^{2++} in the presence of H_2S; Ni–CO complexes can induce C–C bond formation, providing intermediates for carbohydrate or fatty acid synthesis; and the Co–CN–NH_2 system may mimic the primordial reaction environment of vitamin B_{12} [30,30,147]. Hydrogenases ([FeFe] or [NiFe]): catalyze the reversible conversion between protons and hydrogen gas; These discoveries deepen our understanding of the "metal-first" hypothesis, which posits that metal coordination chemistry may have undertaken catalytic and energy management functions before the emergence of organic life [148].

Transition metals Fe, Ni, and Co were enriched in protoplanetary discs through injection from AGB stars and supernovae, providing crucial catalytic nuclei for prebiotic reactions. The metal-organic complexes they formed not only activated small molecules and catalyzed electron transfer but also served as structural and functional prototypes for modern metalloenzymes. This continuity suggests that the core catalytic capabilities of life may have been nascent during the nebular phase preceding planetary formation.

Evidence of Metals in Meteorites: Recorded remnants of protoplanetary disc nucleosynthesis

Modern meteorites, particularly chondrites, are regarded as direct repositories of early protoplanetary disc residues, preserving chemical compositions and material evolution information from the solar system's infancy. They furnish crucial empirical evidence supporting the hypothesis that metallic elements originated from stellar nucleosynthesis and were subsequently injected into the protoplanetary disc.

Composition of Meteorites Rich in Transition Metals

Fe-Ni alloy particles (e.g., meteorites) are widely present in chondritic meteorites, alongside mineral phases rich in transition metals such as Cr, Mn, Co, Mo, and V, including magnetite, olivine, pyroxene, and sulphides [149]. These metals are distributed within the chondritic structure, representing the state of metallic condensation and aggregation within the early solar nebula. Notably, calcium-aluminum-rich inclusions (CAIs) within the Allende meteorite and evidence of radiometallic enrichment within chondrules indicate prior exposure to a high-energy environment containing short-lived nuclides such as 26Al and 60Fe [150].

Anomalous Isotopes Reveal Supernova Injection Events

Non-mass-fractionated isotopic anomalies in elements such as Cr, Ti, and Ni within meteorites indicate these metals originate from nucleosynthesis products of distinct stellar events. For instance, Trinquier et al. identified 54Cr enrichment anomalies in multiple chondrite meteorites, consistent with dust particles formed after a supernova explosion, which confirms the direct injection of supernova material into the solar nebula [149].

Traces of Short-Lived Radionuclides (60 Fe, 26 Al)

^{60}Fe is a typical supernova nucleosynthesis product, and its initial abundance in iron-nickel alloy minerals has been confirmed in multiple primitive meteorites. Research by Tang and Dauphas indicates that the distribution of these metals is linked to the early stratification of the solar nebula, demonstrating their injection and homogeneous mixing into the nebular gas prior to planetary body formation [150,151].

Meteorite Particles of AGB Star Products

Studies of presolar grains within meteorites reveal that carbon-rich particles such as silicon carbide and alumina bear isotopic signatures characteristic of s-process elements from AGB stars (e.g., enrichment in Ba, Sr, Zr, La). It indicates their origin as dust injected by AGB stellar winds, with these particles persisting within the nebula until meteorite formation [141].

R-Process Nuclides and Rare Earth Element Anomalies

Certain meteorites exhibit anomalous ratios of heavy rare earth elements (Nd, Sm, U) formed via the r-process. These signatures suggest possible origins in binary neutron star mergers or specific types of supernovae. Although these heavy metals are not abundant in the solar system, they have profoundly influenced early chemical evolution [152].

Mineral Capsules of the Protoplanetary Disk

Meteorites, acting as "mineral capsules of the protoplanetary disc", preserve the origins, states, and distributions of metallic elements from the solar system's formative era. The diverse metallic phases and isotopic anomalies they exhibit provide compelling support for the following perspectives: Metals within the protoplanetary disc primarily originate from nucleosynthesis products of multiple stellar generations; supernovae and AGB stars constitute the primary injection sources of Fe, Ni, Co, and s-process metals into protoplanetary discs; these metals participated in prebiotic chemistry in atomic, molecular, or dust forms. Consequently, meteorite evidence forms a crucial experimental link in the chain connecting stellar nucleosynthesis to prebiotic chemistry, providing vital geological and astrochemical support for the notion that "life originated from interstellar heritage."

Evidence for the Coexistence of Fullerenes and Metal Complexes

More remarkably, fullerene molecules such as C_{60} and C_{70}, along with their inclusion structures containing rare gases, have been discovered within meteorites [153]. Some studies have also detected indirect signals of metal-encapsulated fullerenes (e.g., $Fe@C_{60}$), indicating that during the condensation process of protoplanetary discs and nebulae, carbon structures, including PAHs and metals, can form stable complexes synergistically [154]. These structures may have served as platforms for primordial molecular adsorption, catalysis, and electronic regulation, acting as "natural test tubes" for prebiotic chemical reactions.

The "Two-Stage Chemical Legacy" in the Murchison Meteorite: An Evolutionary Trajectory from Stellar Discs to Protoplanetary Discs

The prevailing scientific perspective on life's origins posits exogenous input of life-bearing material (meteorites) alongside endogenous emergence (Earth). However, mounting evidence suggests that life arose through a dual process involving exogenous input (the Interstellar Medium, ISM) and endogenous emergence (from a protoplanetary disc). The following analysis actively supports such a dual-process model.

Phase One: Interstellar Precursors Originating from a 7-Billion-Year-Old Stellar Disc

Certain organic compounds within the Murchison meteorite can be traced back to the formation of protostellar systems or star-forming regions approximately 7 billion years ago. This phase may involve the late evolutionary stages of protoplanetary discs around medium-mass stars (e.g., F or G types) or higher-mass stars (e.g., B types). It may also encompass carbon-rich environments following binary star systems or collective stellar storm activity. Relevant interstellar precursor substances include ammonia (NH_3), methylamine (CH_3NH_2), hydrogen cyanide

(HCN), methanol (CH_3OH), and precursor structures of polycyclic aromatic hydrocarbons (PAHs) [12]. These molecules are primarily generated through gas-phase quantum chemical reactions and radical reaction chains induced by high-energy ultraviolet radiation and cosmic rays [155]. They can remain cryogenically preserved within interstellar dust and ice particles for hundreds of millions of years, until they are incorporated into the next round of nebular collapse, serving as the chemical seeds for solar system formation.

Second Stage: Hydrothermal Synthesis within the Solar System's Protoplanetary Disk 4.6 Billion Years Ago

With the formation of the solar system, these interstellar precursor molecules entered the dust- and ice-rich protoplanetary disc [156]. Within parent asteroids or carbonaceous planetesimals, heat sources provided by short-lived radioactive isotopes (such as ^{26}Al) fostered stable hydrated environments. Complex organic synthesis reactions occurred at the water-rock-organic triphase interface. For instance, Strecker reactions can synthesize glycine and alanine in the presence of NH_3, HCN, and aldehyde/ketone molecules, while polymerized HCN chains can generate nucleobases (e.g., adenine, uracil) under suitable temperature and pH conditions [157]. Furthermore, fatty acid-like substances may form through the catalytic hydrolysis and polymerization of small organic molecules such as CO and formic acid, creating membrane-like precursor structures that could have participated in the initial construction of primordial cells.

Murchison Meteorite: A Chemical Bridge Between Two Stellar Systems

The Murchison meteorite stands as one of the most valuable carbonaceous chondrite specimens for research. Its uniqueness lies not only in its rich content of amino acids, nucleobases, PAHs, and isotopically anomalous mineral grains, but also in its preservation of chemical trajectories spanning two distinct cosmological epochs [108]. Interstellar precursor molecules deposited by early protostellar discs underwent hydrothermal transformation within the solar system's protoplanetary disc, culminating in complex synthesis and differentiation within carbonaceous chondrules. This two-stage model – "interstellar input followed by local processing" – clearly demonstrates the formation and accumulation of life precursor molecules at the galactic level, supporting the notion that "prebiotic substances predate Earth's origin".

The Protoplanetary Disk and Interstellar Ice Reaction Mechanisms: From Frozen Molecules to Hydrothermal Chemical Factories

The protoplanetary disc is the gaseous and dusty envelope surrounding a newly formed star, exhibiting rapid variations in temperature, density, and radiation conditions from its centre outward, thereby forming distinct physico-chemical zones. Interstellar ice—primarily composed of ice-coated dust particles containing water, CO, CH_3OH, NH_3, HCN, CH_3NH_2, and other compounds—formed abundantly within molecular clouds before solar system formation, serving as crucial organic seed material entering the protoplanetary disc [158]. These two stages are not isolated but form a continuous chemical evolutionary chain, with key connections manifested in the following aspects:

Interstellar Ice as Molecular Precursors for Organic Reactions within the Protoplanetary Disc

Before the formation of the Solar System, dust particles within the interstellar medium were already coated with numerous condensed molecules (such as H_2O, CO_2, CH_3OH, HCN, and CH_3NH_2), collectively forming "interstellar ice" [159]. Research indicates that these interstellar icy bodies were partially preserved following the collapse of the solar nebula. Embedded within the dust particles that formed the protoplanetary disc, they became a crucial source of the chemical composition of parent asteroids and comets [160].

When these interstellar ices enter warm disc regions or are subjected to impact heating or ultraviolet irradiation, their ice layers sublimate and melt, releasing highly reactive intermediate molecules such as hydroxyl (·OH), methyl (·CH_3), and cyano (·CN) groups. These intermediates, entering liquid water or thermally mineralized environments, can trigger a new round of hydrothermal reactions, thereby forming higher-order organic compounds such as amino acids, nucleobases, and fatty acids [161].

Pyrolytic Encapsulation within Planetesimals: Activation Platforms for Interstellar Ice

In the early stages of formation, miniature celestial bodies within protoplanetary discs (planetesimals, parent asteroids) generate internal heat through the decay of short-lived radionuclides (e.g., 26Al, 40K), raising temperatures to several hundred degrees Celsius [39]. This mild yet persistent heat source provides an ideal environment for the potential synthesis of complex molecules within interstellar ice: alcohols, aldehydes, and ketones in interstellar ice can undergo condensation or reduction to form carbon chains in the presence of hot water; HCN can polymerise into HCN chains or melamine, providing structural precursors for nucleoside bases; CO, HCOOH, and formate molecules can catalyse the formation of fatty acids and their esters on mineral surfaces [162].

Thus, the protoplanetary disc not only inherits the "frozen organic legacy" of interstellar ice but also further processes it through pyrolysis, hydration, and mineral catalysis into more complex molecular forms [163].

Reaction Coupling in Zonal Environments: Chemical Bridging from Icy Shells to Rocky Cores

The physical structure of the protoplanetary disc dictates distinct pathways for organic evolution across different zones [164]:
Outer Disk (>10 AU): Cold, ice-rich. Preserves interstellar ice structure, readily retained in comets
Inner Disk (1–10 AU): Ultraviolet, X-ray, warm Ice sublimation plus Ultraviolet dissociation, initiating radical chain reactions.
Inner Disk (<1 AU): High temperature plus High pressure plus Mineral-rich Hydrothermal reactions, mineral-catalyzed synthesis of complex organics
This zonation structure effectively bridges the low-temperature photochemical mechanisms of the interstellar icy phase with the thermal hydrochemical mechanisms within the protoplanetary disc, enabling a stepwise evolution from interstellar organic seeds to prebiotic molecules [78].

Murchison Meteorite: Physical Evidence for this Bridging Mechanism

Numerous molecular species within the Murchison meteorite exhibit high consistency with interstellar ice simulation products (e.g., glycine, alanine, formic acid, melamine) [59]. Furthermore, anomalies in its stable isotope ratios (D/H, 15N/14N) indicate that portions of its composition inherited the "frozen" isotopic characteristics of the interstellar environment. Moreover, the enantiomeric ratios of specific amino acids suggest that their synthesis occurred within non-equilibrium hydrothermal systems, further supporting the continuous model of "interstellar ice activation and followed by protoplanetary disc processing [38].” Interstellar ice provides the raw material reservoir and intermediates for organic formation; the protoplanetary disc supplies the energy and mineral environment required to drive these reactions. Together, they constitute the upstream and downstream stages in the galactic biochemistry chain, jointly shaping the complex organic systems recorded in carbonaceous meteorites, such as the Murchison meteorite [73]. This connection not only reveals the history of extraterrestrial organic formation but also provides crucial evidence for chemical continuity between the interstellar medium, protoplanetary discs, and Earth.

Prebiotic Chemistry of Transition Metals

Transition metals, due to their unique electronic structures and chemical diversity, are considered to have played a significant role in the molecular evolution that preceded the origin of life. Within high-energy environments, such as protoplanetary discs, they not only form the basis of structural minerals but may also act as catalysts in diverse organic reactions, driving the generation and transformation of prebiotic molecules [165].

Multivalency and Redox Reactions

The d-orbital electronic structure of transition metals confers multiple stable oxidation states. For instance, iron (Fe) can switch between +2 and +3 states, copper (Cu) between +1 and +2, while manganese (Mn) possesses stable states ranging from +2 to +7 [166]. This multivalency enables them to facilitate electron transfer reactions without the need for enzymes, making them pivotal catalysts for primordial redox processes [5].

In experiments simulating early Earth and astrochemical environments, Fe^{2+}-$^{+}$ s and Fe^{3+}-$^{+}$ s are frequently employed to catalyze the transformation of organic acids, aldehydes, nitro compounds, and phosphoric acid derivatives. For instance, Fe^{3+} catalyze H_2O_2-mediated oxidation reactions, whilst Fe^{2++} drive molecular reduction to form amine, alcohol or hydrocarbon intermediates. This redox capability is scarce in enzyme-free systems, highlighting the potential of transition metals as primordial “electron carriers [167].”

Coordination Chemistry Properties and Catalytic Microenvironment Construction

Transition metal ions possess extensive coordination capabilities, forming coordination complexes with diverse geometric structures—such as tetracoordinate, hexacoordinate, and octahedral configurations—with water, carboxylic acids, amines, phosphates, hydroxyl groups, and sulphur-containing functionalities. These coordination interactions not only spatially position reaction substrates but also significantly reduce reaction activation energy by modifying microenvironmental factors, such as charge distribution, acidity/alkalinity, and nucleophilicity [168]. Hydrated silicate, metal sulphide, or oxide particles within protoplanetary discs provided natural binding substrates for metal ions, creating reaction “hotspots” – nanoreactors – between transition metals and adsorbed organic small molecules. This environment may have mimicked later enzyme active sites, providing a template and catalytic foundation for primordial polymerization and condensation reactions [134].

Stabilizing Role of Catalytic Intermediates

In modern enzyme catalysis, reactions often proceed via the formation of highly energetic intermediates (e.g., carboxylation intermediates, peroxides, radicals, enol intermediates) that are extremely unstable in their free states. Transition metals can temporarily ‘capture’ these intermediates through coordination, reducing their decomposition rates and guiding the reaction along favourable pathways.

For instance, Ni^{2++} and Fe^{2++} stabilize adsorbed CO and H intermediates in Fischer–Tropsch-type reactions, thereby promoting carbon chain elongation. Zn^{2++} stabilizes pentacoordinate phosphate intermediates, playing a crucial role in modern nucleic acid polymerases. Thus, the “intermediate trapping” function of such metals holds profound significance in prebiotic chemistry as well [169].

Traces of Metal Enzyme Evolution in Contemporary Life Systems

Modern life systems contain numerous metalloproteins with transition metals as active centers, exhibiting a high dependence on metal ions. It may reflect “genetic traces” of early metal involvement in reactions. Common examples include iron–sulphur clusters (Fe–S clusters), which are present in electron transport chains, nitrate reductases, carboxylases, and other key enzymes, enabling redox reactions and electron transfer. Zinc enzymes (Zn enzymes): Such as carbonic anhydrase, DNA polymerase, and insulin dehydrogenase, which utilize Zn^{2++} to provide Lewis acid centres, stabilizing intermediates and promoting deprotonation. Cu enzymes participate in cellular processes such as pigment oxidation and superoxide dismutase activity, serving as primary metal centers for oxygen activation [170]. Ni enzymes: Examples include methanesequioxygenase and hydrogenases, demonstrating potent catalytic capabilities for reduction reactions and small-molecule transformations.

These enzymes commonly possess complex metal coordination environments that are highly similar to those formed in protoplanetary discs or Earth-like environments, suggesting they may share a common evolutionary origin [171].

From Environmental Catalysis to Enzymatic Catalysis

Transition metals, owing to their multivalency, coordination capabilities, and ability to stabilize intermediates, may not only have driven prebiotic organic reactions within protoplanetary discs but were also ‘borrowed’ and optimized by biological systems during evolution, becoming cornerstones of modern life’s core reaction systems. This continuity ‘from environmental catalysis to enzyme catalysis’ [167] may well represent a profound manifestation of the deep connection between life and the cosmic environment.

Analysis of Prebiotic Chemical Conditions in Protoplanetary Discs

Although interstellar dust (ISM) can undergo chemical reactions under cosmic ray irradiation, producing precursor molecules for amino acids and nucleic acids, Earth itself lacks the conditions for possessing dust and conducting pre-chemical reactions. Nevertheless, the prebiotic conditions necessary for generating key pre-life substances—such as amino acids, nucleic acids, and the precursors for forming cell membranes—can only be realized within protoplanetary discs. Consequently, the physicochemical reactions occurring within protoplanetary disc dust must be repeatedly emphasized as constituting the core of prebiotic chemical reactions. It can be stated that without the physicochemical reactions of protoplanetary disc dust, life would not exist.

Dust Particles and Surface Catalysis

Within protoplanetary discs, dust particles not only serve as the fundamental building blocks for planetary embryos, but their surfaces may also function as crucial platforms for prebiotic chemical reactions. These particles are predominantly composed of iron-rich silicate minerals, such as olivine ((Mg, Fe)2SiO4) and pyroxene ($(Mg, Fe) SiO_3$). Their crystal structures, surface activity, and responsiveness to energy inputs (such as light and heat) provide diverse physicochemical microenvironments conducive to early organic synthesis [172].

Catalytic Functionality of Iron-Rich Silicate Powders

Peridotite and pyroxene minerals belong to the earliest-condensing refractory phases in the solar nebula's condensation sequence. They are thus widely distributed in calcium-aluminum-rich inclusions (CAIs), chondrites, and protoplanetary disc dust. These mineral structures typically contain Fe^{2++} , or Fe^{3+} . At surface defect sites, they provide Lewis acid centres capable of adsorbing gas molecules such as CO, H_2, and N_2. Through surface electron transfer, they induce dissociative adsorption and subsequent reactions. Studies indicate that under simulated solar protoplanetary nebula conditions, these iron-rich silicate powders can simultaneously catalyze two classical reaction pathways [173].

Fischer–Tropsch-type synthesis reactions ($CO + H_2 \rightarrow$ hydrocarbons + H_2O)

This reaction pathway occurs on metallic iron, iron oxide, or ferrosilicate surfaces, serving as a crucial mechanism for synthesizing lower alkanes, alkenes, and aromatics:

$CO + 3H_2 \rightarrow CH_4 + H_2O$
$nCO + (2n+1)H_2 \rightarrow C_nH_{2n+2} + nH_2O$

Within the mid-planetary disc region (1–10 AU, with temperatures approximately 200–600 K), this reaction may proceed on the surfaces of Fe-rich dust particles, particularly when the energy barrier is lowered and reaction rates increase upon excitation by X-rays or UV radiation [174,146].

Hubble-type synthesis reaction ($N_2 + H_2 \rightarrow NH_3$)

Despite the high triple bond energy of N_2 molecules (941 kJ/mol), Fe-rich mineral surfaces provide electron cloud displacement and π-antienergetic orbital coordination capabilities, inducing N≡ N bond activation. Simulation experiments and DFT studies indicate that at low pressure and temperature, Fe_2SiO_4 or FeO-coated mineral surfaces can achieve the following transformation:

$N_2 + 3H_2 \rightarrow 2NH_3$

It implies that iron-rich dust particles within the solar nebula could not only catalyze hydrocarbon synthesis but also facilitate nitrogen reduction processes, providing a natural platform for the generation of ammonia precursors [175].

Multicomponent Reaction: $CO + N_2 + H_2 \rightleftharpoons\rightarrow$ Nitrogen-containing Organics

More remarkably, when CO, H_2, and N_2 coexist within protoplanetary discs, these catalytic surfaces can further catalyze the formation of nitrogen-containing organics (such as methylamine, acetonitrile, and carbamates). Studies indicate that C–N bonds can form via the following steps in the presence of Fe-Si-O active surfaces or FeO clusters:

- CO adsorption + $H_2 \rightarrow\rightarrow \rightarrow$ HCO or CH_x surface intermediates
- Partial dissociation of $N_2 \rightarrow$ N or NH_x active species
- $CH_x + NH_x \rightarrow CH_3NH_2$ (methylamine) or CH_3CN (acetonitrile), etc.

Such reactions require high temperatures and pressures, or artificial catalysts, under terrestrial conditions. However, in protoplanetary discs, they may proceed spontaneously on iron-rich silicate dust surfaces, assisted by UV or radiation [176]. It offers a novel interpretative pathway for the formation of nitrogen-containing organic molecules—precursors to fundamental building blocks of life such as amino acids and nucleobases.

Dust Particles Natural Reactors and Selective Reaction Containers

From a prebiotic chemical perspective, these dust particles serve not only as catalytic platforms but also as "microscopic reaction vessels" with the following advantages: Localised concentration effect: Reagents can be concentrated at the nanoscale, increasing contact opportunities; Reaction site diversity: Surface lattice defects, metal ions, and charge inhomogeneities induce multi-path chemical selectivity; Thermal stability and structural protection: Dust particles buffer radiation and thermal fluctuations, safeguarding intermediates from destruction; Ice-enveloped dust systems: Can coexist with water ice or organic ice, facilitating interfacial reactions and phase-change-induced reaction chains.

Early Formation of "C-H-N" Skeletons Provides Crucial Chemical Pathways

Iron-rich silicate dust particles within protoplanetary discs possess not only Fischer–Tropsch-type hydrocarbon synthesis capabilities but also nitrogen reduction functions akin to the Haber process, even driving the synthesis of nitrogen-containing organic compounds within complex gas systems. This concurrent catalysis of CO, H_2, and N_2 systems positions them as one of the most promising natural reaction platforms in prebiotic chemistry, providing a crucial chemical pathway for constructing the "C-H-N" skeleton during the early stages of life [177].

Experimental Simulations and Theoretical Models: Validating Metal-Catalyzed Prebiotic Mechanisms

Understanding the specific role of metals in prebiotic organic reactions within protoplanetary discs necessitates reconstructing plausible reaction pathways through experimental simulations and theoretical modelling. Over recent decades, multiple simulation experiments utilizing metals such as Fe, Co, and Ni as catalytic centres have demonstrated the potential for forming complex organic molecules under enzyme-free, non-biological conditions. These studies not only elucidate reaction mechanisms at the molecular level but also enable their extrapolation for comparative analysis within protoplanetary disc chemical environments.

Fe/Co/Ni Catalysis in Fischer–Tropsch-Type Reactions

Fischer–Tropsch-type synthesis (FTT) was initially employed industrially to synthesize alkanes and alcohols from carbon monoxide (CO) and hydrogen (H_2) in the presence of metal catalysts. In prebiotic chemistry research, FTT reactions have been extensively utilized to simulate hydrocarbon chain growth processes under primordial planetary or interstellar conditions [146].

Experiments demonstrate that Fe, Co, and Ni catalysts can convert $CO + H_2$ mixtures into straight-chain hydrocarbons, alcohols, and fatty acids under low pressure and elevated temperatures (200–400°C) [178]. In experiments simulating meteorite impact or protoplanetary disc thermal environments, these metals are frequently supported on silicate particles or oxide surfaces, such as Fe_3O_4/SiO_2 or Ni/Al_2O_3, to mimic the physical properties of protoplanetary dust.

FTT products encompass organic compounds with chain lengths ranging from C1 to C18, some of which are structurally analogous to modern fatty acids, esters, and membrane structural precursors, providing potential chemical precursors for the formationof membranes [178].

Haber Synthesis and Nitrogen Precursor Formation

Beyond hydrocarbon synthesis, nitrogen fixation and transformation in primordial environments constituted a critical challenge. The Haber–Bosch process, utilized in modern industry for synthesizing ammonia (NH_3), follows the reaction pathway $N_2 + 3H_2 \rightleftharpoons \rightarrow 2NH_3$, relying on metal catalysts such as iron or molybdenum.

In simulated protoplanetary disc experiments, metal sulphides such as Fe, Fe_3O_4, and FeS can generate ammonia or other nitrogen-containing intermediates under high temperatures and H_2 atmospheres, without requiring high-pressure conditions [179]. Some studies indicate that metal oxides present in protoplanetary discs, including Ti, Fe, and Mo, may also facilitate precursor transformations by adsorbing and activating N_2 molecules on their surfaces. The resulting NH_3 or amine compounds can subsequently condense with organic acids to form amino acid precursors [180].

This reaction system provides an abiotic starting point for amino acid synthesis and may explain the co-occurrence of amino acids and amines in certain meteorites. The Haber synthesis is detectable only within protoplanetary discs, as the conditions favourable for this process were absent in Earth's early environment. Consequently, the Haber synthesis does not apply to the environmental conditions that prevailed on Earth during its primordial era.

Experiments on Metal Coordination Catalysis on Protoplanetary Disc Dust or Mineral Surfaces

Beyond gas-phase reactions, simulation experiments extensively investigate the catalytic capabilities of metal ions on mineral or dust surfaces. By grafting metals (such as Zn^{2++} , Fe^{2++} , Cu^{2++}) onto natural or synthetic silicate, phosphate, or alumina materials, these studies mimic the porous structure and surface coordination sites of protoplanetary disc dust.

For instance, Fioroni and DeYonker modelled the adsorption of Fe^{2+} onto SiO_2 surfaces and its catalysis of the H_2 decomposition and reduction reactions [176]. Similar structures have been observed in iron-rich dust, serpentine, or pyrite. Such models reveal multi-coordination structures between metal centres and hydroxyl groups or organic anions, forming microenvironments analogous to enzyme active sites. This surface catalytic system effectively promotes the following reaction types: esterification of carboxylic acids with alcohols, condensation of amines with carboxylic acids, and dehydration polymerization of phosphates [176].

Although Experimental Conditions Often Require Moderate "Optimization" to Obtain Reaction Products (e.g., elevated temperatures, increased catalyst concentrations), these results retain practical astrochemical comparability. Inner regions of protoplanetary discs (<10 AU) can reach temperatures of several hundred K, harbouring abundant gases such as CO, H_2, and N_2, alongside high-surface-area, metal-rich dust particles.

Furthermore, energy inputs for reactions are provided by the decay of radioactive isotopes (e.g., ^{26}Al), stellar wind heating, and ultraviolet and X-ray irradiation. ALMA observations and comet missions (e.g., Rosetta) have also detected numerous reaction products—including alkanes, ketones, amines, and amino acids—widely present in interstellar ice and protoplanetary material.

Consequently, experiments such as the FTT and Haber reactions, alongside mineral surface catalysis, not only replicate theoretical models but also further validate the actual capabilities of protoplanetary discs in prebiotic synthesis [124].

The Transition from Metallic Elements to Biological Functions

Metallic elements, particularly transition metals, play a pivotal role in enzymeless prebiotic chemistry due to their unique redox activity, coordination chemistry, and ability to stabilize intermediates. The widespread reliance of modern life systems on metalloproteins suggests these metallic functions represent not recent evolutionary innovations, but rather a "hereditary" inheritance of early non-living reaction mechanisms. Understanding the transformative pathways from protoplanetary metallic environments to biochemical functional modules is crucial for elucidating the "continuity" mechanisms underlying life's origins.

The 'Inheritance' of Metals: From Non-Living Catalysis to Retention in Living Systems

Modern life systems exhibit a profound dependence on transition metals as active centres within key enzymes. It includes the role of Fe–S clusters in electron transfer, the activity regulation of Zn^2S in nucleic acid polymerization and deprotonation, and the catalytic functions of elements such as Mo and Ni in nitrogen fixation and methanogenesis [134]. These metalloproteins are conserved across all known life forms, indicating an extremely ancient evolutionary origin predating the establishment of cellular mechanisms.

Experimental simulations demonstrate that during the abiotic prebiotic stage, these metals could already perform functions such as energy conversion, substrate activation, and polymerization reactions on mineral or dust surfaces [182]. Such metallic reaction centers stabilize high-energy intermediates through coordination structures, exhibiting functional characteristics analogous to those of modern enzymes. It suggests that life systems likely "inherited" these non-living catalytic strategies, which were progressively encapsulated and optimized by organic frameworks (such as peptide chains) during molecular evolution, ultimately evolving into today's highly specialized metalloproteins [171]. This "continuous inheritance" from non-enzymatic metal centres to biocatalytic systems constitutes a distinct "chemical inheritance" phenomenon in the origin of life. This transformation of metallic functionality "from non-living to living" may be regarded as a "molecular memory" mechanism in life's evolution: effective chemical strategies were preserved and transmitted through genetic systems, thereby establishing the fundamental framework for metabolism and structure.

Comparison of Metal Availability in the Protoplanetary Disk and Primitive Earth

The primordial Earth, though rich in metallic resources, possessed an early environment (>4 billion years ago) characterized by strongly reducing oceans and an unstable crust. This environment severely limited the bioavailability of numerous transition metals (such as Mo, Zn, Cu) [183]. Particularly under anaerobic conditions, these elements proved difficult to dissolve and incorporate into reaction systems, resulting in a significant deficiency of certain metals within the early geochemical environment.

By contrast, the protoplanetary disc exhibited more uniform elemental distribution and a more complete array of metals. Elements such as Fe, Ni, Mg, and Zn, commonly present in meteorites, planetesimals, and comets in metallic, oxide, and sulphide forms, demonstrate high reactivity under the influence of ultraviolet radiation, radioactive decay, and high-temperature heating [124]. Moreover, these metals often deposit as nanoparticles onto high-surface-area dust or silicate particles, providing natural conditions for the formation of active catalytic surfaces.

Consequently, protoplanetary discs may have provided superior metal availability and catalytic environments for prebiotic synthesis compared to early Earth. It also suggests that some key metallic components essential for life may not have formed endogenously on Earth, but instead completed their birth and evolution within protoplanetary discs before being transported to Earth for further biological evolution.

The Concept of the Protoplanetary Disk as a "Prebiotic Chemical Reactor"

Synthesising analyses from preceding sections, the protoplanetary disc may be conceptualised as a natural "prebiotic chemical reactor" exhibiting several core characteristics: Highly enriched CHNOPS and metallic elements, injected by supernovae, AGB stars, and comets, forming a catalytically potent mixed system; Diverse energy-driving mechanisms, including stellar radiation, high-energy particle irradiation, radioactive isotope decay, and interstellar impacts; A multi-scale reaction environment, ranging from nanoscale dust coordination sites to thermal reaction spaces within planetesimals, capable of satisfying the conditions for complex reaction chains to form; Continuous material cycling and combinatorial experiments, with physical perturbations of the protoplanetary disc (such as disc winds, migration, and collisions) constantly rearranging matter, providing a diverse backdrop for chemical evolution [184,167].

Such environments are not only conducive to individual reactions but particularly suited to combinatorial chemical evolution. Molecules such as fatty acids, peptide chains, and nucleotides can progressively accumulate and undergo selection within the same system, marking the first step toward the origin of life. These conditions converge to form a dynamic, multi-level, modular natural reaction system, akin to a "prototype reactor" preceding biological cells. Within this system, metal catalysis simultaneously influences key reaction pathways across different spatial scales, including carbon chain elongation, nitrogen reduction, fatty acid polymerization, and phosphoester bond formation, thereby enhancing the probability of co-occurrence and selective aggregation of prebiotic precursors.

This hypothesis differs from both Directed Panspermia and any other panspermia theory. The protoplanetary disk origin of life posits that life emerged exclusively within protoplanetary disks, not in other star systems or planetary bodies. Earth's life originated from such a disk, with its core components potentially synthesized and pre-packaged within celestial matter before being delivered to our planet. I term this panspermia theory "planetary disks Panspermia".

Polycyclic Aromatic Hydrocarbons (PAHs) and Complex Organic Compounds

Polycyclic aromatic hydrocarbons (PAHs) constitute a class of hydrocarbons widely distributed throughout the cosmos, typically comprising two or more fused benzene rings. Owing to their structural stability, strong optical activity, and high reactivity diversity, PAHs are regarded as among the most abundant complex organic molecules in the universe. They may play a significant role in the origin of life.

Infrared Characteristics of PAHs and Protoplanetary Disk Observations

PAHs undergo electronic excitation upon ultraviolet irradiation, subsequently releasing energy via infrared radiation. They exhibit characteristic emission features in the mid-infrared region, including: 3.3 μm (C–H stretching vibration); 6.2 μm (C=C skeletal vibration); 7.7 μm (aromatic C–C bond mixed vibration); 11.3 μm (C–H bending vibration) [185].

These features have been observed in protoplanetary discs surrounding numerous young stars, such as Herbig Ae/Be stars and T Tauri discs. The intensity and spatial distribution of PAHs provide insights into the disc's radiation field, gas density, and dust particle evolution [186,187].

Capacity to form π-Complexes with Elements such as Fe, Si, and Ti

The aromatic π electron cloud of PAHs can form π-coordinated complexes with transition metals (e.g., Fe, Ni, Ti) or metalloid elements (e.g., Si). These complexes exhibit the following characteristics: Enhanced stability: Metal ions embed within the PAH ring plane, either donating or accepting electrons to form synergistic bonding; Catalytic centre function: Fe–PAH complexes catalyze electron transfer, radical reactions, or small-molecule reduction; Photoactivity regulation: Metal coordination induces red shifts in PAH absorption bands, broadening the excitation reaction window.

Relevant experimental and theoretical studies indicate: Fe–PAH complexes can mediate redox reactions in the excited state; Ti–Fullerene/PAH complexes have been proposed as the source of the 21 μm infrared feature; Si–PAH π complexes exhibit high spectral matching with interstellar dust infrared features [188,189]. Such complexes may also be regarded as the chemical prototypes of modern metalloproteinase active sites.

PAH Oxidation Products (quinones) and Electron Transfer Potential

Under illumination, ionization, or oxidative conditions, PAHs may form quinone structures, such as naphthoquinone and benzoquinone. These molecules possess the following biochemical significance: Efficient electron acceptors: Quinones can participate in single- or double-electron transfer; Formation of electrochemical gradients: When coordinated with Fe^{2++} / Fe^{3++} or other metals, they can generate primordial electron flows; Precursor function: In modern organisms, quinones (e.g., ubiquinone, coenzyme Q) serve as pivotal electron carriers in respiratory and photosynthetic chains [190]. Thus, oxidized derivatives of PAHs formed within protoplanetary discs may have underpinned early primordial metabolic networks.

PAHs as Structural Templates for Prebiotic Membranes or Primitive Enzyme Systems

Owing to their high planarity, hydrophobicity, and π–π stacking capacity, PAHs and their complexes are proposed to participate in the following structures and functions: Membrane-like self-assembly: PAHs form monolayers or multilayered films at the water-organic interface, resembling precursor lipid membrane; Ordered reaction environments: π–π stacking arranges small molecules, enhancing reaction selectivity; Model for metal-coordinated enzymes: Fe–PAH or Ni–PAH structures may mimic the active centres of primordial reductases (e.g., pre-iron-sulphur clusters) [191,192]. Some studies even propose PAHs as prototypical templates for RNA bases, promoting directional formation or polymerization of purine and pyrimidine structures under UV irradiation.

PAHs rank among the earliest stable complex organic molecules formed within protoplanetary discs. Their high abundance, multi-spectral observational signatures, and capacity for π-coordination with metallic elements, alongside their redox activity, confer a multifaceted potential for catalysis, energy conversion, and structural templating. From complex organic synthesis to protometabolic prototypes and the formation of membrane-like structures, PAHs may represent pivotal intermediaries bridging cosmic chemistry and prebiotic biochemistry.

Polycyclic Aromatic Hydrocarbons (PAHs) and Transition Metals (TMs) in Protoplanetary Disks

In protoplanetary discs, polycyclic aromatic hydrocarbons (PAHs) and transition metals (TMs) jointly participate in multiple pathways of prebiotic synthesis. The formation of metal-organic complexes—such as Fe-PAH, Si-PAH, and TM-carbides/nitrides—has profound implications for cosmochemistry, circumstellar chemistry, and the precursors of life. Within protoplanetary discs and star-forming regions, PAHs interact with abundant transition metals (e.g., Fe, Ni, Co, Cr, Ti) to form complex compound systems. These systems may represent: - Prebiotic organometallic precursors; - Key constituents of protoplanetary disc circumstellar gas/solid matter; - Precursors to early Earth organometallic enzymes and metabolic centres.

Specific Metal-PAH and Prebiotic Chemical Complex Types

Fe–PAH complexes: $Fe–C_{16}H_{10}^{++}$ (cationic) Szczepanski et al., 2006 Potentially serving as templates for early Fe–organic coordination systems involved in electron transfer Si–PAH π-complexes: Si^{+} –PAH composite structures Joalland et al., 2009 Studies on the stability of silicon-aromatic systems in protoplanetary discs, potentially precursors to silicene structures Ti–fullerene adduct: $Ti–C_{60}^{++}$ Kimura et al., 2005, 21μm spectral line Suggests formation of interstellar Ti-organic complexes, potentially linked to early catalysis or electronic structural stability; Oxides such as FeO, Fe_2O_3 Iron oxide clusters formed in stellar winds/disks provide precursors for life's metal enzyme centres, potentially serving as oxygen reduction reaction platforms [193-196].

$Fe–SiO_2$ surface H-grafted structures: Fe^{+} $–SiO_2–H$ indicate chemical catalytic capability on dust surfaces, favouring formation of small molecules like H_2 and HCO; TM-carbides/nitrides: CrCN, FeC, NiN, etc., Brewster & Ziurys ; Sheridan et al. observed antenna fingerprint molecules, which may reveal interstellar gas-phase synthesis pathways [197-201].

Prebiotic Significance of these Structures

Precursors of Primitive Enzyme-Like Structures Comprising Metal Centres

Modern enzymes, such as iron-sulphur clusters (Fe-S clusters), cobalt-vitamin B_{12}, and nickel-carboxylases, all contain transition metals. The aforementioned PAH–TM complexes or oxide clusters have demonstrated pro-enzymatic potential in both molecular structure and function, such as catalyzing CO_2 reduction and facilitating electron transfer.

Formation of Electron Donor/Acceptor Structures Facilitates Primitive Metabolic Network Development

π-conjugated PAHs may serve as electron cloud platforms, interacting with ion centres such as Fe or Ni to form natural redox platforms. In the absence of cell membranes, such structures may facilitate the formation of primordial potential gradients (analogous to modern "energy-coupling membranes").

Catalysis on Dust Particle Surfaces

The binding of TM with PAHs, silica, and ice layers provides physical platforms for interstellar catalytic reaction centres [202]. It facilitates the synthesis of key prebiotic small molecules such as H_2, HCN, and HCOOH.

Why this Constitutes the Astrochemical Frontier of 'Astro-Organometallic Chemistry'

The formation of these complexes falls within the broader domain of astro-organometallic chemistry: whereas past astrochemistry emphasized the inorganic synthesis of small molecules, these results demonstrate genuine chemical interactions—such as coordination, insertion, and adsorption—between organic structures (e.g., PAHs) and metals within protostellar regions and protoplanetary discs. They are no longer "inert molecules", but may form precursor structures akin to biomolecules under electron, photon, and dust catalysis [203]. Such systems exhibit potential structural and functional continuity with coenzymes and enzyme active sites in living organisms.

From "Celestial Inorganic Chemistry" to "Celestial Organometallic Chemistry"

Polycyclic aromatic hydrocarbons (PAHs) within protoplanetary discs and star-forming regions interact with transition metals such as iron, cobalt, and nickel, forming a series of organometallic complexes and oxide clusters. Examples include Fe–PAH and Si–PAH π complexes, FeO clusters, and fullerene metal adducts. Evidence for these compounds is not only clearly demonstrated in infrared and millimetre-wave spectral observations, but their structural and functional characteristics also reveal potential key mechanisms involved in primordial prebiotic chemical reactions. This series of discoveries extends traditional "astronomical inorganic chemistry" into "astronomical organometallic chemistry", enabling us to reinterpret the metal active centres of enzymes, energy metabolism systems, and even selective synthetic pathways for primordial molecules. This perspective is becoming an increasingly vital component within the cosmochemical framework for the origin of life.

Strecker Reaction Pathways and Amino Acid Synthesis Mechanisms in Protoplanetary Discs

The Significance of Strecker Synthesis in Origins of Life Research The Strecker reaction represents a classic amino acid synthesis pathway involving a three-step reaction between an aldehyde (or ketone), ammonia (NH_3), and hydrogen cyanide (HCN), ultimately yielding α-amino acids. This reaction is widely employed in prebiotic chemistry research due to its structural versatility and high efficiency under relatively mild conditions. Research indicates that the Strecker reaction can synthesize common amino acids such as glycine, alanine, and valine under experimental conditions. Moreover, its intermediates (e.g., α-aminonitrile) and end products have been detected in multiple carbonaceous chondrite meteorites, providing direct evidence for its cosmic feasibility.

Strecker Synthesis Reaction Pathway and Reagent Conditions

The fundamental reaction steps of Strecker synthesis are as follows:

- A.The aldehyde (R–CHO) reacts with ammonia to form an imine: $R–CHO + NH_3 \rightarrow R–CH=NH$
- B. Addition of imine with HCN to form imidocarbons: $R–CH=NH + HCN \rightarrow R–CH(NH_2)–CN$
- C.Aminonitrile hydrolyses under hydrothermal conditions to yield amino acids: $R–CH(NH_2)–CN + 2H_2O \rightarrow R–CH(NH_2)–COOH + NH_3$

The raw materials required for the above reaction—HCN, NH_3, aldehydes, and water—have all been observed or inferred to exist within protoplanetary discs, being particularly prevalent in ice–dust particles, interstellar molecular clouds, cometary nuclei, and cometary comas [118,204].

Reaction Platforms and Energy Sources in Protoplanetary Discs

Protoplanetary discs provide highly dynamic and structurally complex reaction platforms: Dust surfaces and interstellar ice shells: In cold environments, HCN and ammonia can form aminonitrile on the surfaces of ice-encapsulated dust particles, exhibiting adsorption capacity and spatial confinement effects; Ultraviolet irradiation and radiation activation: Ultraviolet and X-rays emitted by protostars (such as the proto-Sun) excite molecules within ice to form free radicals, promoting initial reactions; Particle bombardment and radioactive decay: α particles and short-lived nuclides (e.g., ^{26}Al, ^{60}Fe) generate heat sources within planetesimals, sustaining local hydrothermal environments to complete the final hydrolysis steps in the reaction chain; Solar infrared thermal radiation: provides fundamental driving forces for temperature gradients and material transport within the protoplanetary disc, facilitating material exchange between low-temperature and high-temperature regions [205-207].

Co-occurrence of Strecker Intermediates and Products in Carbonaceous Chondrites

Samples such as the Mochisen meteorite and Tagish Lake meteorite reveal not only diverse α-amino acids but also their precursor compounds, including α-aminonitriles, carboxynitriles, and imine derivatives. This chemical fingerprint of "co-occurrence of intermediates and products" indicates that all stages of the Strecker reaction can not only be initiated in the cold cosmic environment but also undergo final conversion within hydrothermal systems inside early protoplanetary bodies (e.g., planetesimals) [208].

Material Cycling and Environmental Regeneration Mechanisms in Protoplanetary Discs

Protoplanetary discs are not static structures but multi-scale matter-energy circulation systems. Dust particles undergo radial and vertical mixing within the disc due to disc winds, gravitational perturbations, and magnetic fields. Cold, icy dust from the outer disc can enter the inner disc, where it receives thermal activation. In contrast, reaction products from the inner disc may migrate hydrodynamically to the outer disc's cold condensation zones, where they can refreeze. The planetesimal formation process encapsulates dust and reaction intermediates within the planetesimal, providing thermal shielding and a water-sealed environment conducive to molecular accumulation and transformation.

Thus, within this dynamic chain of "condensation–activation–migration–transformation–freezing", the Strecker reaction not only has the opportunity to proceed fully, but its distinct stages can occur sequentially at different spatial locations, ultimately forming complete product aggregates.

The Integrative Nature of Strecker Synthesis in the Protoplanetary Disk

The Strecker reaction possesses complete reaction conditions, reactant sources, and energy excitation mechanisms within protoplanetary discs, rendering its feasibility far superior to earlier models positing that "interstellar ice forms only intermediates, requiring Earth's aqueous environment for completion." The disc's illumination, particles, radioactive decay, and temperature gradients constitute a highly integrated chemical reactor capable of in situ synthesis spanning the entire chain from small molecules to amino acids. The product assemblages carried by carbonaceous chondrites represent a "frozen record" of this reaction system. It is therefore reasonable to infer that substantial in situ amino acid synthesis occurred within the protoplanetary disc. These products were subsequently encapsulated within planetesimals, asteroids, and even comets, ultimately being delivered to the early Earth, laying the molecular foundation for the emergence of life.

Environmental Integration for Complete Amino Acid Synthesis in the Protoplanetary Disc and Realization of the Strecker Reaction

Analyses of carbonaceous chondrites, such as Murchison, have repeatedly revealed the coexistence of intermediates (e.g., α-aminonitriles) and final products (e.g., α-amino acids) within the Strecker synthesis pathway. This chemical co-occurrence strongly suggests that the Strecker reaction could not only be partially realized in interstellar ice but also likely underwent its complete three-step reaction chain within the protoplanetary disc [209]. Notably, the liquid water environment required for later hydrolysis can be established within the disc by numerous thermal sources, no longer relying on conditions provided by the early Earth.

The protoplanetary disc harbours an exceptionally diverse and dynamically shifting reaction environment. Spatially, the inner disc (<5 AU) experiences intense stellar radiation and higher temperatures, while the middle and outer regions are rich in low-temperature frozen materials and complex organic compounds. However, due to dynamical processes such as dust migration, gas convection, and disk wind transport, material between the inner and outer regions is in a state of continuous mixing and circulation [210]. Consequently, Strecker intermediates synthesized in the cold zone can be transported to warmer areas for hydrolysis or incorporated into the interiors of planetesimals, forming closed reaction systems within them.

Regarding thermal energy supply, the protoplanetary disc possesses a multi-tiered, multi-timescale energy source system. Firstly, stellar radiation within the disc (encompassing ultraviolet, infrared, and X-ray wavelengths) provides surface heating and drives the decomposition of interstellar ice, activating reaction precursors. Secondly, short-lived radionuclides (such as ^{26}Al and ^{60}Fe) are widely present within the interiors of planetesimals or asteroids. Their decay releases sustained thermal energy over tens of millions of years, maintaining internal temperatures of tens to hundreds of degrees Celsius and a liquid water environment [204]. Moreover, alpha particle bombardment and high-energy electron impacts (e.g., alpha radiation), coupled with tunnelling effects and local exothermic reactions triggered by solar wind particles, can induce precursor chemical reactions within localized dust or ice crystals [12].

Regarding raw materials, all key molecules required for Strecker synthesis have been observed or inferred to exist within protoplanetary discs: HCN, NH_3, CH_4, CO, H_2O, H_2, and others are common molecules found in disc ice layers, gases, or particle surfaces. Particularly in the mid-to-outer regions of the protoplanetary disc ( ), these molecules are extensively present in the form of "ice-coated dust", providing an atomic-scale reaction platform for initiating Strecker reactions [206]. Dust surfaces are rich in catalytic sites (e.g., Fe, Ni, silicates) and generate reactive free radicals under ultraviolet and radiation exposure, significantly enhancing the feasibility of reaction pathways [205].

Therefore, within the multi-scale coupled system of the protoplanetary disc, the Strecker reaction ceases to be a fragmented, sporadic synthesis and should instead be regarded as a highly integrated suite of organic synthesis processes within natural evolution. The requisite reaction substrates, structural platforms, and energy mechanisms were all concurrently established during nebular collapse and disc evolution. It implies that the protoplanetary disc stage already possesses the complete reaction chains, environmental succession, and dynamic flux support necessary for synthesizing multiple amino acids, providing a highly credible chemical foundation for the "non-terrestrial origin" model of life's building blocks.

Prebiotic Mechanisms for Amino Acid Synthesis from PAHs in Protoplanetary Discs, Particularly Aromatic Amino Acids

Astrophysical chemistry and simulation experiments confirm that PAHs are among the most commonly observed organic compounds in protoplanetary discs, exhibiting the following characteristics: planar conjugated structures; high stability; susceptibility to hydrogenation, oxidation, nitration, and carboxylation reactions yielding more complex functional groups; and capacity to serve as carbon skeletons and energy molecules in catalytic and radical chain reactions [58].

Potential Pathways for Amino Acid Precursor Synthesis

- PAHs undergoing ultraviolet irradiation on interstellar ice→ generate functional groups such as carboxyl, amino, and epoxy groups. For example: benzene (C_6H_6)→ phenylpropionic acid→ precursor to phenylalanine.
- Photon/ion bombardment + Ice matrix reactions: simulation experiments demonstrate that complex organic compounds—including aromatic amino acids (Phe, Tyr)—can form upon UV irradiation in cold mixtures (e.g., $H_2O + NH_3 + CH_3OH$ + PAHs); Synergistic effects of high-energy ions injected by supernova explosions and ultraviolet radiation promote ring-opening of hydrocarbon structures and their recombination with nitrogen- and oxygen-containing molecules [211].
- On metal-catalyzed (Fe, Ni, Co) dust surfaces, PAHs undergo transformation: within dust or asteroidal parent bodies, metal oxides (e.g., FeO) catalyze PAH carbon chain cleavage and amino group introduction; reactions with coexisting HCN, NH_3, CO, and CO_2 yield more complex amino acid precursors [212].

Role of Aromatic Amino Acids in Protein Polymerization and Function

Three Primary forms of Aromatic Amino Acids

Phenylalanine Phe–CH_2–C_6H_5 highly hydrophobic, stabilizing protein structures via π-stacking; Tyrosine Tyr–CH_2–C_6H_4–OH capable of forming hydrogen bonds and participating in radical reactions; Tryptophan Trp–CH_2–indole representing the largest aromatic structure, involved in electron transfer and core stabilisation [212].

Influence of Aromatic Amino Acids on Protein Structure

π-π stacking interactions: In lipid-free membrane environments, aromatic residues provide intermolecular stacking forces, aiding the formation of protein aggregates or pre-membrane structures; Construction of hydrophobic cores: Aromatic amino acids tend to cluster inward, driving protein folding and facilitating the formation of enzyme-like structures; Photostability and Radical Scavenging: Tyr and Trp absorb ultraviolet radiation, protecting other structures from damage and potentially catalysing redox reactions.

How do hydrophobic protein aggregates influence nucleotide chirality selection?

It is the most profound question: do proteins or their precursor structures induce chirality selection (L vs D) in RNA/DNA nucleotides? Hypothesized mechanism: hydrophobicity–chirality coupling.

Hydrophobic microenvironments constitute chiral reaction chambers

Hydrophobic aggregates (predominantly composed of aromatic amino acids) may form "chiral-selective microvesicles"; the inner surfaces of these aggregates may preferentially bind L- or D-form nucleotides, thereby inducing a chiral bias before polymerization [213].

π-π Stacking Induces Base Orientation Towards Chiral Template Formation

aromatic side chains may stack with purine/pyrimidine bases; if the amino acid itself favours an L-conformation (as in Earth's L-amino acids), the template it forms is likely to selectively stabilize D-nucleotides (the chiral form utilized by Earth's RNA).

Asymmetry in Microenvironments and Optical Activity Transfer

Experimental and theoretical studies demonstrate that chiral amino acids can induce chirality selection in surrounding achiral molecules, termed "enantioselection"; if primordial protein aggregates were rich in L-aromatic amino acids, their spatial structure may have "transmitted" a chiral bias to nucleotide polymerization [213].

High-abundance polycyclic aromatic hydrocarbons (PAHs) in protoplanetary discs may participate in the formation of complex prebiotic molecules such as aromatic amino acids under conditions of metal catalysis and interstellar ice irradiation. These amino acids establish stable molecular structures through hydrophobic interactions and π-stacking during protein polymerization, potentially forming chiral-selective microenvironments that induce the formation and enrichment of D-nucleotides in RNA and DNA. This process provides a potential molecular bridge explaining the origin of the chiral bias in Earth's life, establishing a continuum from astrochemistry to biological evolution.

The Paradox of the Miller–Urey Extension Experiments

Simulating Earth, Re-enacting the Stellar Disk? The Environmental Mismatch Paradox in Experimental Simulations.

In the mid-20th century, Miller and Urey's experiments first demonstrated that organic molecules essential for life could be synthesized via electrical spark discharges in a reducing gas atmosphere, thereby sparking a wave of prebiotic chemical research. Over subsequent decades, numerous "extended Miller–Urey experiments" replicated and expanded upon these conditions under varied physicochemical settings—including high-temperature hydrothermal reactions, interstellar ice irradiation, proton bombardment, and shock wave oscillations—yielding diverse α-amino acid products to varying degrees.

However, a closer examination of the environments simulated in these experiments reveals a significant paradox: although these experiments are regarded as 'simulating the early Earth environment', their chemical and energy conditions more closely correspond to various natural environmental systems within protoplanetary discs. For instance, organic amino acids and their precursors have been detected in meteorite samples (e.g., Murchison, Murray) [214]. The parent bodies of these meteorites—asteroids or planetesimals rich in ice, organic matter, and transition metals—originated directly from the early protoplanetary disc [215]. Interstellar icy chemistry, simulated in experiments involving the ultraviolet irradiation of ice particles, is highly prevalent in cometary nuclei, dust-enveloped icy shells, and cold condensation zones. High-temperature hydrothermal reactions, though considered representative of Earth's deep-sea hydrothermal vents, are in fact analogous to aqueous thermal environments within protoplanetary disc planetesimals [46,216,217]. These are driven by radionuclides such as 26Al or ^{60}F. For instance, hydrothermal systems within carbonaceous asteroids have been confirmed by terrestrial meteorites [218].

More representative are the gas oscillations, high-temperature catalysis, and $CO/H_2/NH_3$ gas experiments upon which it relies [219]. From a celestial chemistry perspective, this resembles the inner disc environment of protoplanetary discs rich in carbon-oxygen-reducing gases and transition metal particles. Notably, Yoshino et al. simulated amino acid formation from CO, H_2, and NH_3 under high-temperature catalysis [220]. This process closely mirrors the reaction conditions where Fe and Ni-rich dust accumulates in hot zones of protoplanetary discs. Such high-temperature environments with enriched reducing gases and exposed catalysts were absent on the early Earth's surface.

These 'simulated Earth' experiments have inadvertently replicated the physical-chemical systems of distinct reaction zones within protoplanetary discs: interstellar ice irradiation (outer disc), dust catalysis (middle disc), radioactive hydrothermal environments (planetesimals), and thermodynamic pathways involving gas-metal catalysis (inner disc). Notably, high-energy reaction mechanisms such as proton bombardment and alpha particle irradiation represent energy input pathways common in protoplanetary discs but absent on Earth.

Philosophical and Scientific Implications

This phenomenon of "experimental environment mismatching with Earth" challenges the traditional narrative that life's chemistry originated indigenously on Earth. Instead, it supports the view that molecular precursors of life formed within cosmic bodies and were delivered to Earth via meteorites or stardust. This conclusion yields the following scientific insights: Experimental paradigm shift: Many experiments should be redefined as "cosmic prebiotic chemistry simulations"; Enhanced Universality of Life: Should these reactions occur widely in protoplanetary disks, the chemical foundations of life exhibit high cosmic universality; A Continuous Path from Dust to Life: The starting point of chemical evolution is not Earth, but rather the foundations laid within stellar protoplanetary disks.

Consequently, we must reassess the philosophical positioning of the Miller–Urey experiments. They are not merely simulations of "Earth's origin of life," but more likely reproductions of the universal conditions for generating life precursors on a cosmic scale. In this sense, the paradox of the "Miller–Urey extension experiments" is not merely a misdirection in experimental design, but a significant revelation: the molecular foundations of life may have been entirely constructed in the cosmic environment before planetary formation, with Earth serving as a recipient rather than the sole generator of life. The so-called "Miller–Urey extension experiments" more closely resemble an unconscious re-enactment of chemical pathways within cosmic protoplanetary discs than a direct proof of the origin of life on Earth. The true chemical stage was not the primordial Earth, but an earlier, vaster environment—the protoplanetary disc.

Cosmic Precursors of Genetic Systems and Nucleic Acid Formation Mechanisms in the Protoplanetary Disk

Nucleoside Base Precursors in Interstellar and Protoplanetary Disk Environments

The core molecules of the modern genetic system, RNA and DNA, are both composed of nucleoside bases (such as adenine, uracil, and cytosine). These bases can form their precursors—such as HCN polymers, aminoimidazole molecules, and hydroxymethylpyrimidine—in interstellar ice through multi-step photochemical reactions involving simple molecules like HCN, NH_3, and CH_2O [157]. Within the cold condensation environment of interstellar ice (<30 K), ultraviolet radiation drives molecular photolysis and radical rearrangement reactions. Simulation experiments confirm that HCN chains can generate compounds such as melamine and 6-aminopurine. In protoplanetary disc conditions, the likelihood of forming purine/pyrimidine frameworks increases as temperatures rise.

Nucleoside Bases and Ribose Precursors in Meteorites

The Murchison meteorite yielded not only adenine and uracil but also multiple ribose-aldehyde precursors (e.g., ribose-aldehyde, acetyl-ribose), suggesting that these bases could couple with sugars to form the primary stage of nucleoside structures [73]. Sugars are generally considered difficult to stabilize in interstellar ice or protoplanetary discs. However, recent studies have revealed that via the "formaldehyde+ → aldehyde+ → mineral" pathway (such as the Formose reaction), boron-rich aluminosilicate mineral surfaces can effectively catalyze the formation of C5 sugar skeletons. These can then combine with bases to form the initial structure of nucleosides.

Furthermore, research published by Oba et al. in Nature Communications in 2022 detected hexamethylenetetramine (HMT) and its functionalized derivatives [221] for the first time in Murchison and other carbonaceous chondrite meteorites. HMT may be regarded as a crucial precursor molecule for life, hydrolyzing under aqueous conditions to yield key intermediates such as formaldehyde and ammonia. These products are known precursors for the synthesis of amino acids, sugars, and purine bases. This discovery enhances the plausibility of the pathway "interstellar medium → protoplanetary disc → life→ → meteorites → life input to Earth", providing key evidence for the cosmic synthesis of nucleosides and their upstream precursors.

Nucleoside Coupling and Phosphorylation in Asteroid Hydrothermal Systems

Within the warm aqueous environment of parent asteroids, sugars and bases can couple on mineral surfaces to form nucleosides, which further form nucleotides (e.g., AMP, UMP) in the presence of phosphate minerals [164]. Phosphorylation reactions not only provide energy to activate molecules (via high-energy phosphate bonds) but also form the fundamental backbone of RNA chains through ester linkages. Experimental simulations indicate that purine nucleosides, in the presence of Mg^{2++} , can generate small quantities of RNA oligomers (3–10 nucleotides) under conditions of periodic wetting and drying cycles or capillary water flow within rock fissures, suggesting a potential pathway for early "non-enzymatic RNA synthesis".

Indications of a Protoplanetary Disk Genetic System and Molecular Evolutionary Potential

The diverse array of nucleoside precursors in Murchison and other meteorites suggests that the molecular foundation for constructing genetic information carriers existed within protoplanetary discs. Non-enzymatic autocatalytic polymerization, template-directed replication mechanisms, and replication could establish preliminary information transfer models within planetesimals or humid microenvironments. Isotopic ratios (D/H, ^{15}N enrichment) indicate protoplanetary disc origins, lending significance to the protoplanetary disc genetic system within the "pre-RNA world" concept.

These findings suggest that the fundamental structure of genetic molecules did not originate on Earth, but was progressively generated within the cosmochemical evolutionary system comprising interstellar space, protoplanetary discs, and meteorites. It may constitute the physical evidence foundation for a "universal genetic chemistry of the cosmos and protoplanetary discs".

What Ultimately Determines the Chirality of Nucleic Acids (e.g., D-ribose + L-base Combinations)?

An in-depth exploration of the potential mechanisms by which aromatic carbon structures such as PAHs and fullerenes in protoplanetary discs participate in the synthesis of bases (e.g., purines, pyrimidines) and induce their chiral configuration bias ultimately points to a core question: what are the determining factors for nucleic acid chirality (e.g., the D-ribose + L-base combination)?

Mechanisms for Potential Base Synthesis from PAHs in Protoplanetary Discs

PAHs as Carbon Sources or Templates for Base Synthesis

PAHs constitute stable, polycyclic conjugated systems with high cosmic abundance. Under ultraviolet radiation, X-rays, and ion bombardment, they can form aromatic heterocyclic structures containing nitrogen and oxygen heteroatoms. Experiments revealed in interstellar ice simulations that UV irradiation of mixed ice containing PAHs ($H_2O + NH_3 + CH_4/HCN$ + PAHs) generates purine/pyrimidine bases, such as adenine, uracil, and xanthine [222,223].

Reaction Pathways for Base Formation (Exemplary)

$H_2O + NH_3 + HCN \rightarrow \rightarrow$ formamide → pyrimidine skeleton PAHs facilitate this process: - acting as catalytic surface templates; - or providing electron-conjugated platforms in radical environments. Fullerene C_{60} may also fracture under high-energy bombardment, yielding five-/six-membered nitrogen-containing rings (pyrrole, pyrimidine), which can generate complex aromatic isomers on icy or dusty surfaces, approximating modern base skeletons.

Potential Influence of PAHs and Fullerenes on Base Chirality in Protoplanetary Discs

Asymmetric Adsorption Sites on PAH Surfaces Inducing Base Configuration Bias

PAHs themselves are achiral, but when forming asymmetric coordination complexes with metal cations (e.g., Fe^+, Ni^+) or on dust particles (e.g., silicates), they create chiral microenvironments; This chiral environment can selectively adsorb or stabilise a specific configuration of base precursors, analogous to how chiral catalysts induce enantiomers [224].

Fullerenes and Curved Carbon Structures (Curved PAHs) are more Likely to Induce Chirality

Curved π systems (e.g., C_{70}, C_{60}^+) guide neighbouring molecules to stack in specific orientations when forming π-π complexes; Experiments reveal that chiral fullerene adducts interacting with asymmetric ligands (e.g., aromatic amines) stabilise specific chiral base intermediates; such structures may further selectively stabilise nucleosides (base-+ -sugar complexes) with particular configurations through π-stacking and hydrophobic interactions.

What Might be the Ultimate Determinant of Nucleic Acid Chirality (D-ribose, L-bases) in Protoplanetary Discs?

Three Potential Determining Mechanisms: Mineral Surface Induction

Chiral minerals (e.g., orthorhombic calcium carbonate) may selectively adsorb L or D enantiomers, providing the earliest chiral bias templates; Aromatic protein/peptide aggregate templates: Hydrophobic pockets formed by PAH-derived aromatic amino acids preferentially bind D-glycosides, offering molecular-level selectivity amenable to amplification; Autocatalytic asymmetric reactions: Initial minute biases could be amplified via chain reactions (e.g., Soai reaction) without complex enzymes, feasible in early systems [213].

Most Probable Synthetic Mechanism

Within protoplanetary discs, "nucleic acid chirality is determined by a combination of asymmetric physical/chemical factors, including mineral template induction within planetesimals, aromatic/hydrophobic microenvironment selection, followed by amplification via autocatalytic mechanisms". Within the protoplanetary disc, this selection likely first occurs at interfaces rich in polycyclic aromatic hydrocarbons (PAHs) and metals/dust, progressively amplifying the combination of D-ribose and L-bases in environments abundant in L-amino acids [225].

Polycyclic aromatic hydrocarbons (PAHs) and fullerenes within protoplanetary discs not only provide stable, abundant aromatic carbon sources but also establish asymmetric chemical microenvironments within dust particles or icy layers through mechanisms such as π-π stacking, metal coordination, and surface-induced effects. These environments may selectively stabilize specific enantiomers of purine/pyrimidine bases. When combined with hydrophobic aromatic protein templates and mineral surface adsorption mechanisms, this chiral bias may have progressively amplified within early prebiotic chemical systems, providing a molecular origin basis for the universal D-ribose and L-amino acids found in terrestrial life.

Cosmic Origins of RNA and Precursors to Genetic Systems Beyond Amino Acids

Although amino acids were crucial components of early biochemistry, the emergence of genetic systems required the formation of nucleoside bases, ribose, and phosphate groups, which then polymerized into information polymers like RNA. Understanding RNA's chemical origins necessitates exploring synthetic pathways applicable not only to early Earth but also to pre-planetary environments. Increasing evidence suggests that fundamental RNA precursors may have originated from the same astrochemical environments as amino acids.

Astronomical Observations and Meteorite Analyses Reveal the Presence of Multiple Compounds Related to Nucleobases in Interstellar Space: Formamide ($HCONH_2$)

A key intermediate in nucleobase formation, detected in interstellar ice and comets; cyanides (HCN, CN^-): abundantly present in molecular clouds, capable of generating bases such as adenine via condensation reactions; purine and pyrimidine derivatives: including uracil, xanthine, and hypoxanthine, detected in Murchison and other carbonaceous chondrites [226,227]. These findings support the notion that prebiotic bases could be synthesized under abiotic conditions in outer space and delivered to planetary surfaces via meteorites or dust.

Experimental Simulations of Interstellar and Protoplanetary Chemistry

Multiple experimental studies have successfully replicated nucleoside base synthesis under laboratory conditions mimicking interstellar or protoplanetary disc environments: ultraviolet irradiation of formamide or HCN ice layers generates purine and pyrimidine ring structures; radiation-driven reactions form base precursors in simulated interstellar ice-dust environments; Mineral catalytic mechanisms (e.g., montmorillonite) enhance yields and promote selective adsorption of specific bases [228,229]. These findings align with amino acid formation pathways, further supporting the notion that bases and amino acids share a typical origin environment [46].

Ribose Formation and Phosphorylation Challenges

The synthesis of the ribose sugar backbone in RNA is more complex than that of the bases. Although the formaldehyde condensation reaction (Formose reaction) has been proposed as a pathway for ribose generation, it typically yields mixtures of multiple sugars. Recent findings indicate that mineral environments, such as those containing borates, can stabilize the ribose structure, preventing its degradation. Phosphate sources are limited in cosmic abundance but can adsorb onto mineral surfaces. Phosphorylation reactions have been achieved experimentally through heating, urea derivatives, or nitrogen-containing phosphorating reagents , conditions feasible within protoplanetary discs or planetesimals [230].

Preliminary Assembly of RNA-like Structures in Protoplanetary Discs

The co-presence of bases, sugar precursors, and phosphate sources has been detected in meteorite samples, suggesting that RNA precursors may undergo partial polymerization within the following cosmic microenvironments: hydrated mineral pores within planetesimals; ice particle surfaces under ultraviolet radiation or heating/cooling cycles; transient liquid water zones within protoplanetary discs or locally molten environments created by impacts [231]. Although achieving complete RNA chain polymerization under natural conditions remains challenging, the cosmic synthesis of these RNA precursors significantly lowers the threshold for subsequent polymerization on Earth.

The Origin and Distributional Significance of the Genetic System

Suppose RNA precursors indeed originate from protoplanetary discs. In that case, this implies that the fundamental building blocks of genetic systems are not Earth-specific, but rather naturally occurring chemical structures throughout the cosmos. This perspective supports the “cosmic seeding” model, which posits that the chemical building blocks necessary for life were already present during the early stages of planetary formation. This continuity from disc chemistry to biological genetic function suggests that the genetic basis of life may be a natural product of disc-level chemical evolution, possessing universality across numerous planetary systems within the Milky Way.

Hemolithin: A Key Component Linking Protoplanetary Disk Chemistry and Early Life Metabolism

Protein Discovery in Meteorites: New Evidence for Cosmic Chemistry

In the Acfer 086 meteorite discovered in 1990, a collaborative team of scientists from Harvard University, PLEX Corporation, and Bruker Scientific reported the discovery of a complete protein structure previously unobserved on Earth, named Hemolithin [232]. It exhibits the following unique characteristics: Primarily composed of glycine, the simplest known amino acid; Protein terminals feature regularly arranged Fe, O, and Li atomic structures; Iron oxide clusters at the protein tip possess photon-absorbing capabilities, enabling photosynthesis-like energy dissociation reactions (e.g., water splitting into H_2 and O_2); This structure has never been observed on Earth but recurs in multiple carbonaceous chondrite meteorites, including the Allende meteorite.

Potential Functions of Hemolithin: A Bridge from Metabolism to the RNA World

Primordial Metabolic Initiator

Hemolithin may absorb photons via ferrocene clusters to catalyze water splitting, generating hydrogen and oxygen [233]. It serves as a primary energy source for chemotrophic microorganisms in environments deprived of light. It may constitute substantial support for the “metabolic primacy model”, wherein metabolic mechanisms predate the origin of RNA or DNA genetic systems [9].

Scavenger of the RNA World

Hemolithin may participate in removing by-product water molecules during RNA synthesis, facilitating phosphodiester bond formation. Its surface electronic structure may serve as an energy relay for RNA chain polymerization while stabilizing the local polymerization microenvironment [234].

Anchoring Agent in the F–S world

Its iron content reacts with sulphides to guide the formation of iron-sulphur clusters, anchoring early metabolic units in the “iron–sulphur world hypothesis”; its lithium content may regulate electron density and reactivity, providing stability for primitive electron transport chains in anaerobic environments [235,236].

Connections to Electrotrophic Bacteria

Its structure resembles the ferritin-like electron transfer system in modern electrotrophs; it serves as a chemical fossil for understanding the transition from non-biological electrocatalysis to primordial microbial electron metabolism.

Chemical Evolutionary Sites Originating within Planetesimals

Iron, lithium, and glycine could coexist via Strecker reactions with metal catalysis within protoplanetary discs; Radioactive decay of ^{26}Al and ^{60}Fe within planetesimals provides a sustained heat source, maintaining aqueous environments and localised melting, creating thermochemical conditions for Hemolithin synthesis; planetesimal impacts and protoplanetary disc migration mechanisms may have disseminated Hemolithin as “seeded organic structures” across multiple planetary systems [237-239].

Hemolithin is not merely a peculiar organic structure in meteorites; it may represent a primordial protein template with energy-releasing capabilities, providing energy, structural support, and electron transfer functions before RNA polymerization and during the early establishment of metabolic mechanisms. This protein could also serve as a “molecular fossil” for modern ferro-oxygenase, photocatalytic clusters, and metal enzyme centres.

The Birth and Evolution of Protoplanetary Disk Life in Relation to Quantum Mechanics

Quantum mechanics exhibits multifaceted connections with the origin and evolution of protoplanetary disc life. Each link in the chain—"nuclear decay (→), charged particle/γ transport and deposition (→), ultrafast excitation/solvation in media (→), chemical reaction branching (radiolysis/tunnelling/spin chemistry)→ Prebiotic chemical networks", each link carries distinct quantum physical and quantum chemical mechanisms; a few of these mechanisms also extend into what is commonly termed "quantum biology" (primarily referring to the sensitivity of spin-related reactions to weak magnetic fields, etc.) [240].

Quantum Physics: Nuclear Decay and the Quantum Nature of Particle Behaviour

Alpha Decay is Fundamentally Quantum Tunnelling

Alpha clusters escape by traversing the Coulomb potential barrier; quantum tunnelling through the nuclear potential barrier (Gamow theory). For instance, the alpha decay half-life of ^{238}U (4.47 billion years) is directly determined by the probability of barrier penetration.

Beta Decay is Governed by the Weak Interaction

Gamma radiation is emitted via nuclear energy level transitions. The atomic mass deficit $\Delta E = \Delta mc^2$ constitutes the fundamental source of energy for all subsequent heating/chemical processes [240]. For instance, the neutron → proton + $e^{-}+ \bar{\nu}_e$ process involves: W boson exchange (quantum field theory); chiral symmetry breaking (left-handed neutrinos); the β^- decay of ^{40}K (89% branch) exemplifies this. Radioactive elements (particularly ^{40}K) constitute significant contributors to thermal sources within small celestial bodies.

Quantum Decoherence of Nuclear Excited States

α/β/secondary electrons deposit energy through ionization and excitation in ice/water/minerals, theoretically described by quantum scattering cross-sections and $-dE\,/dx$ (Bethe–Bloch/path structure); this step "grounds" nuclear energy as local heat and excitation. Energy deposited into water is quantified by the G value and kinetic network(predominantly thermalized within picoseconds to microseconds, with a minor fraction temporarily stored as chemical potentials in H_2, H_2O_2, etc.).For instance, in the electron capture (EC) decay of 53Mn, the nuclear excited state (~5.4 keV) de-excites via internal conversion electron or X-ray emission, a process governed by Fermi's golden rule transition probability [241-244].

Molecular/Condensed Matter Ultrafast Processes (Quantum Chemistry)

The "Photostability" of Nucleosides Depends on Non-Adiabatic Transitions at Conical Intersections

After excitation, they rapidly return to the ground state within picoseconds, reducing photodamage probability. It is a classic quantum chemical/non-adiabatic kinetic effect, equally significant in ice/solvent environments. In ice/minerals, the quantum behaviour of condensed-matter excitations, such as excitons/defect states/polaritons, also plays a role, determining how energy propagates through the medium and triggers chemical reactions [246]. HCN polymerization (forming purine/pyrimidine bases).

Hypotheses and Conjectures Regarding NH_3 in Protoplanetary Discs

Why are ancient and present-day Earths rich in N_2, whilst protoplanetary discs contain almost no N_2 in either gaseous or icy phases?

Within the protoplanetary disc (and planetesimals), due to the ionizing radiation (α/β/γ or heavy ions) from cosmic rays and their isotopes acting upon nitrogen- and hydrogen-containing mixtures, coupled with the disc's abundance of transition metals and other catalytic metals, the most reliable targets for "bombardment/radiolysis" to generate NH_3 primarily fall into two categories:

The N_2 + H_2O (ice/liquid phase) system: ionizing radiation first radiolytically decomposes water to yield potent reducing agents (dissolved electrons $e^{-}_{a\varphi}$, H·). These reactive species can progressively reduce N_2 to NH_3 (via intermediates such as N_2^{-} , N_2H, N_2H_2, N_2H_4, etc.). Recent γ-ray "radiocatalysis" experiments confirm that, in the presence of metal catalysts such as Ru, ammonia can be synthesized directly from N_2 + H_2O under ambient to moderately pressurized conditions, achieving NH_3 concentrations in the millimolar range. The core mechanism involves $e^{-}_{a\varphi}$ generated by water radiolysis driving N_2 activation and hydrogenation. This pathway has classical validation: γ-radiolysis experiments in the 1960s already yielded NH_3 from N_2 and H_2O [247]. Protoplanetary disks rich in H_2 (H_2, hydrogen-containing organics, or reductive species from water radiolysis) and/or metal mineral surfaces favour the reductive pathway [248]. In the N_2 + H_2 (gas phase) system, pure gas-phase N_2/H_2 slowly generates NH_3 under Co-60 γ-ray irradiation; the yield increases linearly with absorbed dose and exhibits measurable dependence on N_2 and H_2 partial pressures (representing a "radiolysis-mediated" ammonia synthesis pathway) [249,250].

Thus, it may be stated that within protoplanetary discs and their planetary disc planetesimals, gamma-ray photolysis or gamma-radiation catalysis induced by cosmic and solar radiation alongside gamma rays emitted by isotopes leads to the production of NH_3 – the product of the Haber experiment – through bombardment by cosmic and solar radiation and isotopes. This process fills the protoplanetary disc with NH_3 rather than N_2. It fully reflects the radiation environment within the protoplanetary disc and planetary disc, as well as planetesimals, which is entirely distinct from that on Earth. I shall elaborate on this in greater detail in the subsequent chapter, "The 'Radiation-Metabolism Coupling' and 'Radiation-Metabolism Coevolution' Hypotheses Regarding the Origin of Life".

Reaction Pathways and Cryogenic Chemistry (Tunnelling/Surface Reactions)

Upon 10–30 K ice in the protoplanetary disc, numerous pivotal hydrogenation reactions are propelled by quantum tunnelling of protons/hydrogen atoms [251]. Examples include the CO → →H_2CO→ and CH_3OH sequence [252]. These represent the "adiabatic" prebiotic chemical key steps [253]. Alpha particle bombardment may induce proton tunnelling ($H \rightarrow^{+}$, hopping within enzyme precursor molecules), potentially accelerating primordial metabolic reactions.

Quantum Biology: Spin Chemistry and Weak Magnetic Field Sensitivity (Bridges to Quantum Biology)

Radical Pair Mechanism

Short-lived radical pairs generated by radiolysis and photochemistry undergo coherent spin exchange between singlet and triplet states, yielding products potentially sensitive to geomagnetic fields (~50 μT) [254]. This spin dynamics, governed by quantum-coherent hyperfine coupling, has been employed to explain avian magnetoreception. In prebiotic environments, it implies that (weak) magnetic fields and isotopic nuclear spins may fine-tune branching ratios of certain radical reactions, thereby influencing the spectrum of organic products.

Electron/Proton Transfer Networks (Marcus Framework)

At the interface between Fe–S minerals/clusters and organic ligands, the rate and directionality of electron transfer can be characterized by Marcus theory (recombination energy, driving force, electron coupling), determining the "impedance matching" of prebiotic redox networks [255]. It represents a classic paradigm coupling quantum and statistical perspectives.

Key Implications for "Life's Origin and Evolution"
Energy budget: Quantum processes at the nuclear level provide energy; quantum deposition and thermalization at the condensed matter level determine the "available" power density [256,257]. A small fraction of energy is "refrigerated" within chemical bonds (e.g., H_2, H_2O_2) for subsequent chemical energy utilization [258].

Reaction Accessibility
Tunnelling opens pathways at low temperatures (e.g., methanol precursor synthesis); Non-adiabatic ultrafast relaxation enhances photostability of key biomolecules (facilitating accumulation); Spin chemistry may fine-tune product selectivity in weak fields. Network Directionality: Electron transfer between mineral/metal centres and organisms follows Marcus rules, determining which pathways are more "favourable" and influencing the sustainability of premetabolic prototypes.

In summary, the isotope decay–radiolysis–prebiochemistry chain is founded end-to-end upon quantum principles; yet "quantum biology" typically denotes quantum effects within living systems (e.g., radical-induced magnetic sensing) [259]. For the prebiotic stage, it is more apt to state that quantum physical/chemical mechanisms determine energy deposition, reaction pathways, and selectivity, thereby establishing boundary conditions and preferences for life's origin [260].

Source of life's Energy: F=ma and $\Delta E = \Delta m \times c^2$

Dust within protoplanetary discs undergoes continuous dynamic motion. Dust particles interact with one another while being influenced by the disc's overall physical and chemical conditions, which vary due to differences in particle mass, density, and inherent physicochemical properties. Protoplanetary disc dust is subjected to diverse cosmic and protosolar radiation, including but not limited to infrared, visible light, ultraviolet, X-rays, gamma rays, and alpha and beta rays from isotopes. Consequently, the birth of life within the protoplanetary disc—its intricate physicochemical transformations—can be quantified, and this quantification is reproducible. This quantification differs from the crude descriptions of volcanic eruptions, celestial lightning, deep-sea hydrothermal vents, and so-called 'black smokers' on ancient Earth. The energy source for life can be broadly described by two equations: F=ma and $\Delta E = \Delta m \times c^2$. These equations are not merely simplistic descriptions of physical phenomena; they also provide profoundly insightful interpretations of the origin of life.

F=ma on the Protoplanetary Disc

Mechanical-Chemical Coupling in Dust Collisions within Protoplanetary Discs:
From F=ma to Prebiotic Chemistry: This paper systematically summarizes the kinetic factors governing dust particle collisions in protoplanetary discs alongside their chemical consequences (mechanochemistry, radicals, and plasma). It provides applicable equations and illustrative examples [261].

Physical Framework and Variables

- **Mass:** $m = (4/3)\pi\rho r^3$; ρ (density) for silicates typically taken as $3000\ \mathrm{kg\cdot m^{3}/^{-}}$ [262].
  Peak deceleration: $a(max) \approx v(rel)^2/(2\delta)$; (where a is contact radius, material-dependent). Note: δ denotes contact compression displacement (~10^{9}–10^{-6} m), v(rel)is relative velocity, and r is particle radius.
- **Peak force:** $F(max) \approx mv(rel)^2/(2\delta)$; Relative velocity: v(rel): Induced by turbulence, differential drift and gas drag, typically 10^{-9} m/s to 10^{-6} m/s (spanning mild adhesion to violent fragmentation).
- Compression displacement (contact flattening scale): δ; nanometre–micrometre scale (10^{-9}–10^{-6} m) [263].
- **Effective curvature:** R^*; collision of two spheres of equal radius r, $R^* = r/2$.
- **Effective elastic modulus:** E^*; given by two materials E, ν as $E^* = [(1-\nu_1^2)/E_1 + (1-\nu_2^2)/E_2]^{-1}$, with silicate approximated as 50 GPa [264].

F = ma and impact dimension (F=ma and three core quantities)
Peak acceleration: $a_{max} \approx v_{rel}^2 / (2\delta)$
Peak force: $F_{max} \approx m\, v_{rel}^2 / (2\delta) = m \cdot a(max)$
Kinetic energy (reduced mass μ): $E_k = \frac{1}{2} \mu\, v_{rel}^2$ (for identical particles, $\mu = m/2$)
Momentum and impulse: $J = \int F\, dt \approx \mu \cdot \Delta v$; Contact time t(c). See Hertz approximation [265-267].

Upper limit of body temperature rise (if all kinetic energy is converted to heat): $\Delta T_{max} \approx v_{rel}^2 / (2\, c_p)$, where for silicate $c_p \approx 800\ \mathrm{J\cdot kg^{-1}\cdot K^{-1}}$.
Typical parameters: $\rho(silicate) \approx 3000\ \mathrm{kg\cdot m^{3-}}$; r: μm–cm; v(rel): 10^{-2}–$10\ \mathrm{m\cdot s^{-1}}$ (from turbulence, drift and differential speed); δ: 10^{-9}–10^{-6} m; contact time ~ μs; volume heating is typically negligible, but flash heating and high shear may occur in the contact zone.

Hertz Contact Approximation and Impact Timescale
Contact radius: $a = (3 F R^* / 4 E^*)\ (1/3)$
Peak contact pressure: $p_0 = 3F / (2\pi a^2)$
Displacement-contact radius relationship: $\delta \approx a^2 / R^*$
Impact duration (empirical approximation): $t_c \approx C \cdot (m(eff)^2 / (R^* E^{*2}\ v(rel)))\ (1/5)$, $C \approx 2.9$, $m(eff) \approx \mu$
Note: The above represents the dimensional relationships for elastic contact; when plastic/brittle fracture occurs, the values of a, p_0, and tc will deviate, but the order-of-magnitude assessment remains valid [268-270].

The Causal Chain from Mechanics to Chemistry
From Mechanics to Chemistry: Three-Stage Velocity–Particle Size Effect Spectrum.

Low-Velocity/Microparticles
Bonding/sintering, slight compaction, minimal fragmentation; surface fluctuations→ expose fresh active sites. Chemistry: Rapid surface area growth; low-coordination sites exposed in Fe–S/ metal oxides↑ ; microporous networks facilitate water/ice film microreactors; supports prebiotic processes like FTT/CO hydrogenation.

Medium-Speed/Millimetre Scale
Bouncing/compaction/partial fragmentation ("bounce barrier"); contact point pressures (ppp) reaching hundreds of MPa–GPa. Chemistry: Coexistence of mechanochemistry (bond breaking/ defects, E'/F centres) and triboelectricity; ice/organic ice: generation of H, OH, H_2, H_2O_2 and other radiolysis-induced homologous radicals (synergizing with radiochemistry). PAHs/ Organics: Dehydrogenation/cationization/oligomerization; Fe–S: Cracking exposes Fe^{2+}/Fe^{3+} and sulphur radical sites, promoting surface reactions of $CO/CO_2 \rightarrow$ organics. Charged dust enhances discharge/microplasma probability, further driving precursor

formation (CN/HCN/NO_x, etc.).

High-Velocity/Millimetre–Centimetre Scale

Severe fragmentation/jeting, contact pressures reaching GPa; bulk heating remains low, but flash temperatures in contact zones+ exhibit pronounced high shear. Chemistry: Surface area of newly formed debris increases dramatically →, causing a leap in catalytic site density; Mechanistic chemical chain reactions: Free radicals generated by fragmentation undergo secondary reactions within micro-pores/films, promoting methylation, carbonylation, alcoholation, etc.; Volatile re-evaporation: Trapped CO, CO_2, H_2, CH_4 desorb, replenishing gas-solid phase reactions.

Note: Particle-particle collisions alone are insufficient to achieve "globule melting" (which requires larger-scale energy sources, such as intra-disk shock waves or lightning); however, collisions prepare reactive species and structures, coupling with radiative/photochemical drivers.

Net Effects and Impacts on Prebiotic Chemistry

Structural Effects

Crushing + Compaction → Hierarchical pore formation and "microchamber" creation, enhancing reactant enrichment and selectivity, and improving diffusion-retention equilibrium [271]. GPa-level contact pressures + Microsecond-scale shear → Lattice defects, bond breakage, and active site exposure (e.g., E'/F centres) [272].

Surface Chemistry

Freshly Exposed Surfaces and Defects → Low-coordination metal/sulphur sites, enhancing reaction rates for FTT, CO/CO_2 reduction, nitration/sulphidation pathways.

Radical/Plasma Coupling

Mechanochemistry + Triboelectricity → Parallel radical and electrochemistry, generating key precursors like HCN, H_2O_2, peroxy radicals [273,274]. Mechanochemistry: Generation of radicals including H·, ·OH, H_2, H_2O_2 on ice/organic ice surfaces; dehydrogenation/ionization/polymerization of PAHs [275,276]. Friction Electrification and Microdischarges: Charged dust-dust/dust-gas discharges, yielding electrons/ions, NO_x/HCN precursors, and peroxy radicals [277-280].

Synergy with Radiochemistry

Collision-released active sites and radicals provide "landing sites" for radiolysis products from $^{26}Al/^{60}Fe$ isotopes, jointly driving a dual-track prebiotic environment of H_2/CO supply + ROS pressure. Radiolysis-generated H_2, ·OH, H_2O_2 from ^{26}Al, ^{60}Fe interact synergistically with collision-activated surfaces/radicals [281].

Velocity–Particle Size–Chemical Outcome Matrix

Interval	Mechanical Outcomes	Surface/Structure Effects	Chemical and Prebiotic Effects
Low-speed/microparticles: $v \lesssim 0.1\ m \cdot s^{-1}$, $r \sim \mu m$	Bonding/compaction; minimal fragmentation	Exposure of fresh active sites; formation of microporous networks/thin-film water layers	Enhanced surface catalysis; favourable for FTT, CO/CO_2 hydrogenation; reactant enrichment
Medium-speed/millimetre scale: $v \sim 0.1–1\ m \cdot s^{-1}$, $r \sim 10^{-4}–10^{-3}$ m	Bouncing/compaction/partial fragmentation; contact pressure p reaching $10^2–10^3$ MPa	Defects and bond breakage (E′/F centres); triboelectric charging	Mechanochemical radicals (H·, ·OH, etc.); PAH dehydrogenation/ionisation; Fe–S site exposure → CO reduction; micro-discharges → HCN/NO_x precursors
High-velocity/millimetre–centimetre: $v \sim 1–10\ m \cdot s^{-1}$	Intense fragmentation/jet; contact zone "flash temperature" and high shear	Massive new surface area; hierarchical porosity	Chain radical reactions (methylation/carbonylation/alcoholation); volatiles desorption replenishing CO/H_2/CH_4; synergistic effects with radiation/photochemistry

Radiation Environment and Energy Injection Mechanisms

In the quest to understand the origins of life, the source and transfer of energy remain pivotal to constructing prebiotic chemical reaction networks. The protoplanetary disc's cosmic environment was highly dynamic, saturated with diverse high-energy radiation and radioactive nuclides, delivering energy far exceeding most natural sources in the modern terrestrial environment. This energy, conveyed through radiation, ionization, and thermal transfer, provided essential conditions for the synthesis, excitation, and transformation of organic molecules.

Thermal Energy Released by the Decay of Short-lived Isotopes such as ^{26}Al and ^{60}Fe

Protoplanetary discs harbour several short-lived radionuclides (SLRs), notably: 26Al (half-life≈ 0.7 Myr), 60Fe (half-life≈ 2.6 Myr) [14,240]. These nuclides are believed to originate from supernova explosions or the injection of Wolf-Rayet stellar winds. They are widely distributed throughout the disc, being incorporated into planetesimals, dust, or ice grains. Their decay pathways involve β^+ or β^- , releasing high-energy electrons, γ-rays, and heat, adhering to the mass-energy relationship: $\Delta E = \Delta m \times c^2$.

Estimates indicate that 26Al decay can deliver approximately 6×10^5 J/kg of localised thermal energy, equivalent to sustaining heating on a planetoid scale for several million years. This induces the following reaction environments: localized hydration reactions (H_2O + minerals), thermal restructuring of organic matter, melting of the ice layer, and the formation of complex organic compounds (such as amines, alcohols, and aldehydes) within enclosed environments [282]. Thus, SLRs provide a crucial, temporally controllable, spatially localized, and energetically concentrated driving force for "chemically active zones" within protoplanetary discs.

Exposure of the Protoplanetary Disk to Cosmic Rays, X-rays, Ultraviolet and Gamma Radiation

Protoplanetary discs are exposed to intense interstellar radiation environments, primarily comprising: Cosmic rays (CRs): High-energy protons and heavy ions with formidable penetrating power, capable of penetrating hundreds of metres of solid material; X-rays and Ultraviolet radiation (X-UV) Intense radiation originating from the central young star (T Tauri or Herbig Ae/Be), with intensities hundreds of times greater than the present-day Sun; Gamma rays (γ-rays): introduced by supernova remnants or neutron star winds, possessing extremely high ionising capability [105,283,284].

These rays can induce diverse primordial reactions within dust particles, ice layers, and organic films, such as molecular excitation and dissociation, radical generation, carbon chain cleavage and restructuring, and alterations in surface electronic states (e.g., PAH oxidation). Particularly in environments where dust particles coexist with water ice, radiation-induced reactions can trigger complex pathways, such as H-abstraction, radical-radical coupling, and photoreduction, thereby forming biologically relevant groups, including amino acid precursors, aldoses, and amines [246,39,286].

Radiation-Induced Reactions and Radical Mechanisms

Experimental and theoretical studies indicate that the following reaction pathways may occur concurrently under radiative and photochemical conditions:

- $CO + H_2O + UV \rightarrow\rightarrow \rightarrow HCO\cdot, \cdot OH\rightarrow \rightarrow H_2CO\rightarrow \rightarrow CH_3OH$
- $HCN + \gamma\rightarrow \rightarrow CN\cdot + H\cdot\rightarrow NH_2CN$ (aminonitrile)
- H_2O ice + high-energy particle→ $\cdot OH + H\cdot\rightarrow H_2O_2, HO\cdot, H_2$

These radical reactions require neither high temperatures nor catalysts, being driven solely by high-energy electrons or photons. Consequently, they can occur in the cold outer regions of protoplanetary discs. Such conditions are virtually absent on Earth's surface but are the norm in protoplanetary discs, particularly beyond the 'snow line' [286].

The high-energy environment of protoplanetary discs is more chemically active than Earth

Compared to modern Earth, protoplanetary discs possess several significant high-energy advantages:

Conditions	Protoplanetary Disk	Early Earth
Ultraviolet intensity	High (young stellar activity)	Attenuated by atmosphere
X-ray flux	High	Virtually absent
Radiation-induced radical formation	Abundant	Scarce
Dust catalysis/ice-encapsulated particle structure	Widespread	Rare
Internal heat sources within SLRs	Present ($^{26}Al/^{60}Fe$) [25]	Primarily terrestrial core radioactivity

These discrepancies suggest that the radiation environment within protoplanetary discs is not merely destructive but also synthetic—providing a unique reaction space and excitation mechanism for the formation of primordial organic systems.

The decay of radionuclides within the protoplanetary disc, combined with stellar radiation and cosmic rays, collectively form a high-energy, sustainable, multi-modal energy input system. Whether through heat-induced reactions triggered by 26Al decay or radical reaction chains induced by ultraviolet radiation/cosmic rays, these processes could facilitate the transition of primordial organic chemistry in environments devoid of enzymes, high pressure, or biological involvement [123]. Such energetic conditions may have held greater potential for creating "pre-life systems" than those present on early Earth.

Radioactive Isotopes in the Protoplanetary Disc: A Core Factor in Life's Origin and Evolution

Radioactive isotopes within protoplanetary discs play a central role in research on the origin of life within these discs. Due to their predominantly heavy metallic nature, both short- and long-half-life radioactive isotopes had migrated mainly into the Earth's core or mantle during the early formation of the primordial planet. Those present in the crust exhibited extremely low abundances. When the primordial Earth's crust was still molten, these short-lived radioactive isotopes had already been depleted, rendering them insignificant for the origin of life. However, within the protoplanetary disc, both short- and long-lived radioactive isotopes played a pivotal role in the emergence and evolution of life within the disc. The critical role of isotopes in life's evolution will be discussed in detail in Part VI.

The "short-lived (SLR) and long-lived radioactive isotopes frequently discussed in early solar system studies" are organized into two tables, detailing: half-lives, primary decay types/radiation, and common radiochemical products when this radiation bombards different targets (H_2O, C–O, (CO/CO_2)/carbonyl-containing), Fe–S mineral clusters, and PAHs.

The SLR list is based on the isotopic review in Protostars & Planets VII, supplemented with standard geochronological systems; half-lives are based on recent measurements. Radiochemical "products" refer to the typical major products, with specific distributions dependent on experimental conditions such as temperature, phase state (ice/aqueous solution/solid), dose, and mixing with other molecules [287]. Summary of Radioisotopes and Radiochemical Products in Protoplanetary Discs:

Short-Lived Radioactive Isotopes (SLRs)

Isotope	Half-life	Decay / Radiation	Typical Irradiation Products (by Target)
^{7}Be	53 days	EC, γ	H_2O: e^- aq, H·, ·OH, H_2, H_2O_2; C–O ice: HCO, H_2CO, CH_3OH; Fe–S: Fe^{3+}/S·; CO2; PAHs: ionisation, CO, CH4 dehydrogenation [288-290]
^{10}Be	1.387 Myr	β^- , γ(weak)	As above
^{26}Al	0.717 Myr	β^+ /EC, γ(1.809 MeV)	As above, enhanced high-energy γ radiation decay
^{36}Cl	0.301 Myr	$\beta\text{-}^{-} \rightarrow {}^{36}Ar$; EC$\rightarrow {}^{36}S$	Ibid.
^{41}Ca	0.10 Myr	Electron capture (X-ray/Auger)	Ibid.
^{53}Mn	3.7 Myr	$\beta^- \rightarrow {}^{53}Cr$	Ibid.
^{60}Fe	2.6 Myr	$\beta\text{-}^{-}$ ($\rightarrow {}^{60}Co \rightarrow {}^{60}Ni$), γ	Ibid.
^{107}Pd	6.5 Myr	$\beta\text{-}^{-} \rightarrow {}^{107}Ag$	Ibid.
^{129}I	15.7 Myr	$\beta\text{-}^{-} \rightarrow {}^{129}Xe$, γ	Ibid.
^{146}Sm	68 Myr	$\alpha \rightarrow {}^{142}Nd$	Ibid.
^{182}Hf	8.9 Myr	$\beta\text{-}^{-} \rightarrow {}^{182}W$	Ibid.
^{205}Pb	Variable	EC	Ibid.
^{244}Pu	80 Myr	α	Ibid.
^{247}Cm	15.6 million years	α	Ibid.

Long-lived Radioisotopes

Isotope	Half-life	Decay / Radiation	Typical Irradiation Products (by Target)
^{238}U	4.47 Gyr	Alpha chain, beta, gamma	H_2O: e^- aq, H·, ·OH, H_2, H_2O_2; C–O: HCO, H_2CO, CH_3OH; CO, CH4 CO2,Fe–S: Fe^{3+} , S·; PAHs: ionization[288,290]
^{235}U	0.704 Gyr	α chain	Ibid.
^{232}Th	14.05 Gyr	Alpha chain	As above
^{40}K	1.25 Gyr	$\beta\text{-}^{-}$, EC	As above
^{87}Rb	48.8 Gyr	β^-	Ibid.
^{147}Sm	106 Gyr	α	Ibid.
^{176}Lu	37.8 Gyr	$\beta\text{-}^{-}$, EC	Ibid.

Brief Introduction to Isotope "Products from Bombardment of Different Targets"

- **H_2O (liquid/ice):** e^- _aq, H·, ·OH, H_3O^+ , H_2, H_2O_2; at high doses/in mixtures, O_2, $HO_2\cdot/O_2^-$. These constitute the elementary product spectrum under all ionizing radiation (α, β, γ, and secondary electrons) [288].
- **C–O systems (CO/CO_2 with $H_2O/CH_4/CH_3OH$ ice mixtures):** HCO, H_2CO, HCOOH, CH_3OH, CH_4, CO_2 (mutually interconverting), and more complex organics; products strongly influenced by composition and temperature [291].
- **Fe–S (pyrite/FeS/biogenic sulphide clusters):** ·OH, H_2O_2-induced $Fe^{2++} \rightarrow Fe^{3++}$, S(0)/polysulphide anions, surface radicals and electron transfer; under anoxic conditions, radiolysis products may drive "anoxic pyrite oxidation" and ROS generation [292].
- **PAHs:** Ionization (PAH^+ /PAH^-), dehydrogenation/rehydrogenation, fragmentation (commonly Cn^+ carbon clusters and small hydrocarbon fragments), configurational isomerization and surface effects (low-energy surfaces, high-energy bulk phases); concurrently occurring with cosmic ray/ion irradiation and VUV/UV photochemical reactions [293].
- **Mixed ice (H_2O: CO/CO_2:CH_4:NH_3 etc.):** Cosmic ray/heavy ion irradiation leads to the destruction and resynthesis of precursor molecules, with observed formation of H_2CO, H_2O_2, CH_4, HCOOH, etc., accompanied by sputtering/desorption [294].

Within protoplanetary and planetary disks, isotopes of varying half-lives—both long-lived and short-lived—not only induce diverse chemical reactions in surrounding matter by emitting different types of radiation and particles, but also generate internal heating effects within the disk particles themselves. It enables reactions and subsequent life forms to adapt and evolve within the disk particles. Isotopes heat disk particles through two distinct mechanisms [295].

Radioactive Decay

The spontaneous transformation of atomic nuclei releases energy (α/β particles, γ photons, nuclear recoil, and trace neutrinos).

Radiolysis

These radiation species ionize/excite surrounding matter (commonly water, ice, or organic compounds), breaking chemical bonds and generating new chemical species (·OH, H·, H_2, H_2O_2, etc.) [288].

The two represent a cause-and-effect relationship: decay provides energy and particles, while radiolysis constitutes the chemical and thermal effects resulting from these particles depositing energy into the medium [296].

At which stage does the heat generation mechanism occur?

At the Instant of Decay

Energy is released in the form of kinetic energy of charged particles (α/β), γ photon energy, subatomic nucleus recoil energy, and neutrino energy. These are not yet heat (they are the energy of ordered particles/photons).

Particle "Braking" (Energy Deposition) within the Medium

Charged particles transfer energy to surrounding molecules via ionization/excitation (described by "linear energy transfer" or LET, dE/dx), rapidly (on the femtosecond–picosecond timescale) converting to random thermal motion and generating heat. If γ photons are absorbed via photoelectric effect/Compton scattering/pair production, their energy is first transferred to electrons, which then deposit energy as described above to produce heat. Neutrinos interact scarcely with matter, their energy largely escaping without generating heat. Recoiling subatomic nuclei in solids also rapidly transfer kinetic energy to the lattice, producing heat.

Conclusion

Primary heat is generated during the process of "particle/photon interaction with the medium and subsequent halting", not "at the moment of emission". Decay merely "loads energy into the bullet/photon"; the actual heat generation occurs when the bullet strikes the target and dissipates its energy as heat.

Radiolysis and Heat Distribution

Within the same deposited energy, a portion is used for bond breaking/generating free radicals and molecules (chemical work), yet the vast majority ultimately dissipates as heat. Chemical energy "stored" (e.g., H_2 produced by water radiolysis, or the separation of H_2O_2/O_2 in) will release heat upon subsequent reaction/recombination; this merely retrieves chemical potential energy previously "deposited" by radiation, without creating additional energy ex nihilo [244].

How should "decay heat" versus "radiolysis heat" be understood?

Decay-Induced Heating

Calculating the energy budget from the source perspective = (number of decays per unit time) × (energy deposited per decay in the medium) [297].

Radiolysis Heating

Describing the consequences of the same energy deposition from the target material's perspective: Ionization/excitation→ Free radicals and chemical products + Heat. Chemically, the G value (number of molecules produced per 100 eV) is commonly used to describe yield. So-called "radiation-induced heat generation" either involves the immediate conversion of the entire energy deposit into heat or the temporary storage of part of the energy as chemical potential, later released as reaction heat. The conservation of energy constrains the entire process [298-300].

Relationship between particle type and heat generation

Alpha particles: Short range, high linear energy transfer (LET), with energy almost entirely deposited within micrometre scales→. Localized intense radiation+Significant heat generation [301]. Beta particles (electrons/positrons): Longer range, moderate linear energy transfer (LET), with energy deposited over larger volumes→. Heat generation is dispersed [302]. Gamma rays: Uncharged, requiring prior absorption/scattering before transferring energy to electrons; Significant heat production in high-density/thick media; substantial escape possible in sparse media [303]. Neutrinos: Virtually no heat production, negligible [304].

Protoplanetary Disk vs. Early Earth: Comparative Energy Advantages for Life Origins

"Which environment—protoplanetary discs or the early Earth—favoured life's emergence?" requires quantitative comparison across four dimensions: energy source sustainability, diversity, intensity, and chemical driving capacity. The following presents a comprehensive analysis.

Persistence of Energy Sources

Protoplanetary Disk and Disk Planetesimals, Radioactive Isotope Decay (e.g., ^{26}Al, ^{60}Fe, ^{40}K) Time Scale: Short-lived nuclides (e.g., ^{26}Al's 710,000-year half-life) provide burst energy early on; long-lived nuclides (e.g., ^{40}K's 1.25-billion-year half-life) sustain prolonged heating [24,260]. Spatial distribution: Uniformly distributed within the planetesimal, unaffected by surface conditions. Stellar radiation (protoplanetary Sun): Continuous ultraviolet and X-ray bombardment of dust particles drives photochemical reactions (e.g., PAH dissociation).

Early Earth, Transient Energy Events

Volcanic eruptions (hours-months), lightning (microseconds), meteorite impacts (instantaneous). Submarine hydrothermal vents (lifetime ~ tens of thousands of years, highly localized) [305]. Solar energy: Surface ultraviolet radiation (but the early atmosphere lacked the ozone layer, which most scattered/absorbed) [306].

Conclusion

Energy release from the protoplanetary disc exhibits global and sustained characteristics (on a million-year timescale), far surpassing the transient events of the early Earth.

Diversity of Energy Forms

Radiation Types in the Protoplanetary Disc

Form of Energy	Mechanism	Life-related products
α/β rays (isotopes)	Bombardment of $H_2O \rightarrow H_2 + H_2O_2$	Energy source (H_2) and oxidising agent (H_2O_2) [307]
Ultraviolet/X-rays (stellar)	Dissociation of CO/CH_4 to generate free radicals	Activation of organic molecules (e.g., carboxylic acids)
Infrared radiation (dust)	Heating ice particles to 100–300 K	Promotion of ice-phase organic reactions (e.g., formaldehyde polymerization)
Cosmic rays	Induction of deep-matter radiolysis	Continuous H_2 generation within the star

- Synergistic effect: Coupling of radioactive decay heating ($\Delta E=\Delta m\times c^2$) with dust dynamics (F=ma) drives material cycling.

Early Earth: Primary energy sources: geothermal (localized), lightning (random), solar (attenuated by atmosphere) Limitations
Single energy form with uneven spatial distribution (e.g., hydrothermal vents confined to mid-ocean ridges).

Conclusion
The protoplanetary disc offers richer energy forms whilst simultaneously supplying both reducing agents (H_2) and oxidizing agents (H_2O_2), fulfilling the redox coupling requirements of life chemistry.

Energy Intensity and Chemical Driving Capacity
Quantitative Comparison

Parameters	Protoplanetary Disk	Early Earth
H_2 Production Rate	10^8–10^{10} molecules/g (rock)/ yr (α decay) [308]	10^6–10^7 (serpentinization)
Temperature gradient	50–200°C within planetesimals (persistent)	Hydrothermal vent 350°C (localized)
Free radical flux	OH· concentration ~10^{5-5} M (photolysis of water)	<10^{-7} M (lightning/ ultraviolet)

Prebiotic Chemical Efficiency, Protoplanetary Disc
Synergistic action of radioactive+ and ultraviolet radiation can enhance PAHs→amino acid conversion rate by 100-fold [309]. Fe-S cluster minerals (e.g., greigite) catalyze $CO \rightarrow CH_4$ under α irradiation [29]. Early Earth: Hydrothermal vent Fischer-Tropsch reactions required high temperatures and pressures, yielding limited products (primarily alkanes).

Conclusion
Protoplanetary discs possessed greater energy intensity and could drive more complex chemical networks.

Comprehensive Energy Advantage: The Protoplanetary Disk Prevails
Core Advantages: Sustained Energy Supply
Radioactive decay provides stable energy input over hundreds of millions of years. Global Coverage: Radiation permeates throughout the protoplanetary disc, eliminating "dead zones". Redox Equilibrium: Simultaneous generation of H_2 (reduction) and H_2O_2 (oxidation) surpasses Earth's strongly reducing environment.

The 'Golden Window' for Life's Origin
The Protoplanetary Disk " Timeframe: 1–10 Myr after disk formation (^{26}Al activity period). " Spatial Scope: Micrometre–metre scale within planetesimals (radiation shielded + liquid water microenvironments). Early Earth: Timeframe: Intermittent energy events during the Hadean Eon (>4.0 Ga). Spatial Scope: Confined to hydrothermal vents/shallow water zones.

Quantitative Comparison
The energy flux density of the protoplanetary disc may have been 10^2–10^4 times that of the early Earth (*based on the ^{26}Al thermal model of meteorites*).

Interpretation of Formulas
he Life Significance of F=ma and $\Delta E = \Delta m \times c^2$

- F=ma:
  Describes dust dynamics within planetesimals—particle collisions (acceleration a) drive organic matter aggregation (e.g., lipid membrane self-assembly) [310].
- $\Delta E = \Delta m \times c^2$:
  Radioactive decay (mass loss Δm) converts into thermal/ chemical energy (ΔE), driving prebiotic chemical reactions. Examples: ^{14}C decay (β^-)→ Nitrogen ionization → HCN formation → Purine synthesis [311]. In summary, protoplanetary discs comprehensively surpassed the early Earth in terms of energy continuity, diversity, and chemical drive efficiency, making them a more ideal cradle for the origin of life.

The Protoplanetary Disk as Cradle of Life
The Irreplaceability of the Protoplanetary Disc as Life's Cradle
Self-organization effects in dynamic dust systems: profound application of F=ma. Dust collision dynamics
micrometre-scale particles (mass m) coalesce via van der Waals forces within turbulence (acceleration a), forming fractal structures [263]. Selective Screening: Mass gradients induce dust stratification, concentrating organic matter at pressure nodes [312].

Quantitative advantage of sustained radiative energy,
- The biological significance of $\Delta E = \Delta m \times c^2$:
- ^{26}Al decay: 1 kg of ^{26}Al decay releases 4.5×10^{13} J (≈10^7 years of sustained energy supply), sufficient to maintain 10^{15} litres of water in liquid form (calculation in Lichtenberg et al., 2021) [260].
- By comparison, Earth's most significant volcanic events (e.g., the Toba eruption) release only 10^{18} J over <1 year.

Synergistic Network of Energy Forms

Energy Type	Flux (erg/ cm²/s)	Life-related products	Terrestrial Analogue Efficiency
Alpha rays (^{238}U)	10^6–10^8	$H_2 + H_2O_2$ (redox pair)	No equivalent
Ultraviolet (primordial Sun)	10^4–10^5	PAHs→nucleotide precursors [313]	100 times lower
Cosmic rays	10^2–10^3	Deep H_2 (penetrating stars)	Negligible

Unique Properties of Stellar Particles as "Life Reactors" Radiation-Chemistry Coupled Microenvironment
Water photolysis chain reaction:
H_2 O —alfa— H2 +OH. (G=0.5),
α-particle irradiation of H_2O: H_2 yield (G value = 0.45 molecules/100 eV)
OH. +CO→CO2 +H.

- Efficiency 10^4 times higher than hydrothermal vents [29].

Geometric Growth of Chemical Diversity, Fe-S Mineral Catalysis
Irradiation-generated nanoscale Fe_3S_4 (lattice constant 5.23 Å) can simultaneously catalyze: $CO \rightarrow CH_4$ Thiopeptide bond formation (*cysteine polymerization, Bonfio et al., 2020, Sci. Adv.) [314,315]*.

Temporal Scaling and the Prebiotic Chemical Window
Liquid water persistence within protoplanets: 10^6–10^8 years (^{26}Al+^{40}K decay heat). Terrestrial hydrothermal systems: <10^5 years (destroyed by plate tectonics).

Disruptive Evidence Challenging Traditional Geocentric Paradigms

Isotopic fingerprinting: Coexistence of ^{60}Ni (^{60}Fe decay product) with organic matter in meteorites [316]. Molecular clock data indicate that the back-calculated time for LUCA (Last Universal Common Ancestor) (4.3 Ga) predates Earth's solidification (4.0 Ga)—insights from extremophiles: Desulforudis audaxviator survives solely on radiant energy [317,318].

Reproducible Experimental Validation

JAXA Asteroid Simulation Chamber: Under 10^{-6} Pa vacuum + α-source irradiation, H_2O → amino acids conversion achieved (efficiency 10^{-4}) [319]. ETH Radiation Chemistry Model: Predicts the discovery of RNA precursors within asteroids with a diameter greater than 50 km [320].

The Inevitable Consequence Pointed to by the Laws of Physics

- $F=ma$ → Dust self-organizes to construct precursor factories for life.
- $\Delta E=\Delta m\times c^2$ → Nuclear decay provides the perfect sustained energy source.

Protoplanetary disc planetesimals, as life incubators simultaneously satisfying energy sustainability and chemical complexity, demonstrate superiority beyond the geocentric paradigm.

Divergence between the RNA World Hypothesis and the Metabolic Primordial Hypothesis

Mechanisms for PAH Synthesis and Base Formation in Protoplanetary Disks: Potential Chemical Bridges from Aromatic Carbon Structures to Life's Chirality

The Enigma of Transition from Achiral Molecules to Chiral Life Systems

Earth's life systems exhibit a pervasive high degree of chiral bias, with nearly all natural amino acids being L-configured and nucleic acid sugars being D-configured. This "molecular chiral unity" constitutes one of life's fundamental characteristics, yet its emergence within primordial chemical environments remains a key unresolved question in science. Its origin must be considered and traced back to the enzymeless, non-coding prebiotic environment. Given the widespread presence of aromatic carbon structures such as polycyclic aromatic hydrocarbons (PAHs) and fullerenes in protoplanetary discs and interstellar media, this paper explores the potential role these molecules may have played in base formation and nucleotide chirality selection. It further connects this to mechanisms involving hydrophobic protein aggregates, which facilitate the subsequent selection and amplification of nucleotide chirality. An attempt is made to establish a bridge between prebiotic chemistry in the cosmos and the biochemistry of life on Earth.

Potential Chemical Pathways for Base Formation from PAHs in Protoplanetary Discs

PAHs as Providers of Interstellar Aromatic Carbon Skeletons

PAHs are ubiquitous in interstellar dust, stellar winds, comets, and protoplanetary discs, constituting approximately 10–20% of interstellar carbon [58]. Their planar aromatic skeletons are stable and highly reactive, rendering them well-suited for chemical synthesis under high-energy radiation.

Base Formation Experiments in Interstellar ice/dust Environments

Introducing PAHs into cold ice layers (containing H_2O, NH_3, CH_4, HCN, etc.) and subjecting them to ultraviolet radiation or ion bombardment can induce the formation of nucleobases such as adenine (A), uracil (U), and xanthine (X) [222]. PAHs serve not only as reaction substrates but may also function as electron-conjugated templates, stabilizing transition states [223].

Representative Experiments

Synergistic Effects of Fullerenes and Heterocyclic Carbon Structures

Spherical aromatic structures such as fullerenes (e.g., C_{60}) exhibit high stability in interstellar environments. Upon high-energy excitation, they can cleave into nitrogen-containing five-membered/six-membered rings, forming precursor frameworks for bases or inducing molecular stacking orientation, thereby establishing a foundation for subsequent stereoselectivity.

Mechanisms of Aromatic Carbon Structures Inducing Base Chirality

Metal–PAH Complexes form Asymmetric Microenvironments

Aromatic structures themselves are not chiral, but can induce chiral environments. The π-complexes formed between metal ions (e.g., Fe^+ , Ni^+) and PAHs (e.g., Fe–PAH) exhibit spatial asymmetry, creating adsorption platforms that favour specific enantiomers: π–π stacking surface energy confers binding advantages for particular base conformations; The spatial induction effect between fullerenes and curved aromatic molecules, where asymmetric stacking of curved structures (e.g., C_{70}, C_{60} derivatives) exerts stereoselective influence on neighbouring molecular conformations, holds promise for introducing chiral bias during early base synthesis stages; metal-containing PAH complexes exhibit sensitivity to structural configuration in mass spectrometry and infrared experiments [194].

Synergistic Selection with Chiral Sugars

Bases ultimately link to pentose sugars (e.g., D-ribose) via glycosidic bonds. Asymmetric surface microenvironments formed near PAHs or fullerenes can influence the energy barriers for binding D- or L-form nucleosides, thereby constituting an initial source of chiral bias.

Further Selection of Nucleotide Chiralities by Aromatic Hydrophobic Protein Aggregates

Aromatic Amino Acid Sources and Early Polymerization

Within protoplanetary discs, PAHs may further participate in amino acid synthesis, particularly in the formation of aromatic amino acids such as phenylalanine (Phe), tyrosine (Tyr), and tryptophan (Trp) [321]. These amino acids form early protein-like aggregates through hydrophobic interactions and π-stacking.

Chiral Recognition Mechanism of Hydrophobic Pockets

As illustrated in Figure 1, these protein aggregates may form spatially compact hydrophobic pockets with the following functions: distinguishing D-/L-ribose or base enantiomers; forming asymmetric bonds via hydrogen, hydrophobic, and π interactions; and inducing specific conformational aggregation to enhance the reactivity of chiral molecules. This mechanism bears a striking resemblance to modern enzyme chiral recognition patterns, suggesting that chirality selection may originate from structural self-assembly during the non-coding polypeptide stage rather than later gene-regulated processes. Recent experiments have further revealed that introducing asymmetric conformations within hydrophobic polypeptide microenvironments promotes unidirectional chirality preferences in nucleotide polymerization [322]. Model systems simulating primordial Earth or interstellar dust environments (such as mineral templates or protein aggregate surfaces) have demonstrated selective adsorption and steric hindrance effects.

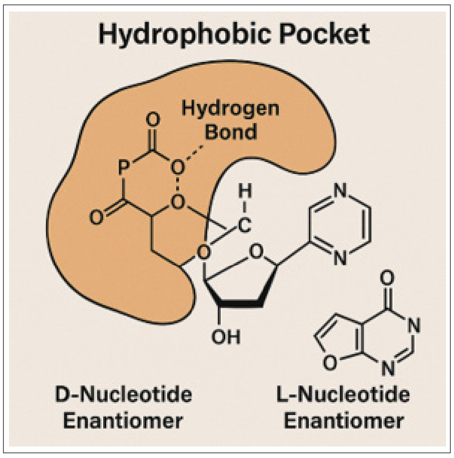

Figure 1: Chiral recognition mechanism of hydrophobic pockets

Amplification of Chiral Selection and Evolutionary Significance

Sources of initial bias may originate from selective adsorption on crystalline mineral surfaces; asymmetric binding at PAHs–metal–dust interfaces; or spontaneous chiral enrichment (e.g., Soai reaction) [225,213].

Mechanisms of Bias Amplification

Aromatic hydrophobic pockets create more stable polymerization environments for specific chiral molecules via non-covalent interactions; once a biased pathway for D-ribose–L-amino acid formation emerges, it may be further amplified by autocatalytic networks (e.g., chiral nucleoside polymerization). It provides a physicochemical basis for the dominant "D-sugar/L-amino acid" structure in terrestrial life.

Chemical Continuity Between Aromatic Carbon Structures and Biological Chirality

Abundant PAHs and fullerenes in protoplanetary discs not only provided aromatic templates for life precursors like bases and amino acids, but may also have established chiral microenvironments through mechanisms such as π-π stacking, surface induction, and metal coordination. During subsequent molecular aggregate evolution, non-covalent recognition pockets formed by hydrophobic protein aggregates likely further selected and amplified specific enantiomers, ultimately unifying life's chiral structures. Together, these processes constitute an evolutionary pathway from cosmic disordered molecules to ordered biological information systems.

Transition from Physical Selection to Chemical Evolution

This mechanism of chiral recognition, based on hydrophobic protein aggregates, not only provides a potential molecular platform for explaining the D-bias in ribose and nucleic acids, but also bridges the transition from 'physical preference' to 'chemical coding' in the origin of life. In other words, the early stages of life may not have relied on specific enzyme systems, but instead progressively established the selectivity and directionality of molecular systems through simple spatial matching and non-covalent interactions.

Overall, aromatic amino acids generated from polycyclic aromatic hydrocarbons (PAHs) within protoplanetary discs or early Earth environments may have formed spatially selective non-covalent binding pockets via hydrophobic protein aggregates, thereby enabling preferential adsorption of nucleosides or sugars with specific chirality. This mechanism not only provides a molecular basis for explaining the bias towards D-ribose and L-amino acids in modern biological systems, but also further emphasizes the selective role of molecular self-organizing structures in the origin of life, serving as an evolutionary bridge "from physical chemistry to biological information."

Transition from Prebiotic Chemistry to Genetic Systems

The Establishment of the RNA World and Pathways for Molecular Informationalization – The Leap from Chemical Reactions to Information Systems.

Previous chapters have examined how polycyclic aromatic hydrocarbons (PAHs) and fullerenes in protoplanetary discs participated in synthesizing bases, amino acids, and precursor protein structures, potentially inducing molecular chirality bias. However, life requires not only structural and functional molecules but crucially the capacity to store, replicate, and mutate genetic information. This chapter examines, from a chemical evolution perspective, the potential pathways for the formation of the RNA world and how a non-coding molecular system evolved into a genetic system with informational function and selectivity.

Nucleotide Formation and RNA Precursor Assembly

Separation and Coupling of the Three-Part Synthesis Pathway for Nucleotides

Nucleotides comprise a pentose sugar (e.g., D-ribose), a base (purine/pyrimidine), and a phosphate group. Their formation pathways may be spatially and temporally separated

- **Bases:** Synthesised in PAH+HCN+NH_3+H_2O interstellar ice irradiation experiments;
- **Sugar:** D-ribose formed via the Formose reaction involving formaldehyde (HCHO);
- **Phosphate:** Phosphates formed during volcanic, mineral, or meteorite impact processes, potentially activated on mineral surfaces [45-323,324].

Key issues in the assembly pathway: How to achieve the stereoselective linkage of sugars, bases, and phosphate?

Potential Pathways and Catalytic Assistance for Nucleoside Formation

Experiments indicate that PAHs, binding with divalent metals (e.g., Mg^{2++}, Fe^{2++}), can catalyze base-sugar linkages on simulated interstellar dust surfaces [325]. Specific RNA residues (e.g., 5'-AMP) may even form spontaneously under non-enzymatic conditions and accumulate during wet-dry cycles [326].

Origin of Primitive RNA Polymerization and Replication

Enzyme-free RNA Polymerization Reactions

Studies indicate that activated nucleotides undergo template-directed polymerization under dehydrated conditions, on cold ice surfaces, mineral surfaces (e.g., montmorillonite, serpentine), or in hydrophobic peptide environments [225]: Conditions for forming phosphodiester bonds are mild; sequence replication bias is small but non-zero, providing variability; and they exhibit catalytic activity and folding capability.

"Functional Randomness" of Primitive RNA Sequences and Subsequent Selection

RNA chains initially lacked specific functions, instead accumulating sequence diversity through "chemically heterogeneous polymerization". Through environmental selection and autocatalytic feedback, stable structures with weak catalytic functions—termed "functional prototypes"—gradually emerged.

Establishment of the RNA World and Functional Expansion

The Multifunctionality of RNA forms the Core Basis of the RNA World Hypothesis

RNA can both store information and catalyse its own reactions (such as self-cleavage and autocatalysis), making it the only molecule in modern biology possessing this "dual identity": ribozymes such as ribozyme ligase, RNA polymerase ribozyme, etc.; Co-factors for primitive amino acid activation and peptide bond formation; phosphate exchange reaction catalytic model [327,4].

Three-stage Model of Transition from the RNA World to DNA–Protein Systems

RNA replication system: RNA molecules undertake coding+ and catalysis; RNA+protein symbiotic system: Random peptides begin participating in co-catalysis and structural stabilisation; DNA-mediated storage system: DNA gradually replaces RNA in information storage due to greater stability and replication fidelity, with RNA transitioning to an "intermediary molecule" role [328,329].

Emergence of Molecular Information Encoding and Sequence Selection Mechanisms

Emergence of Sequence–Function Correlations

As RNA lengthened and structures became more complex, specific sequences favoured folding into stable three-dimensional structures, exhibiting: self-protection (degradation resistance); simple catalytic capabilities (e.g., ligation, cleavage); and the ability to form ordered complexes with metal ions or amino acids/peptide segments. These functional sequences became "progenitors of genes".

Replication Bias, Mutation, and Selection Loops

Minor sequence variations arising during replication gradually established selection–amplification–evolution loops through environmental screening. Early on, there was no clear boundary between "gene–protein" information and function; information and function were fluid and interchangeable.

Chemical Origins and Evolutionary Dynamics of Information

The genetic information system did not emerge through mutation, but instead gradually developed as a new functional dimension during chemical evolution. Prebiotic chemistry dominated by PAHs within protoplanetary or planetary discs not only provided fundamental structural molecules but also created the physical and chemical context for information encoding. The RNA world, as a transitional phase, offers a compelling mechanistic explanation for life's leap from random chemistry to ordered coding.

Potential Mechanisms for RNA Structural Selectivity and Chiral Induction by Fullerenes in Protoplanetary Discs

The Chiral Puzzle of the Primitive RNA World

The RNA World hypothesis posits that life originated from an RNA-centred self-replicating and catalytic system. However, this model confronts a critical question: why does nature favour the D-ribose structure (i.e., dextrorotatory nucleotides)? In non-chiral-inducing environments, synthesized nucleotides should form racemic mixtures of D/L enantiomers. Yet, all modern life utilizes D-ribose, indicating that a chiral selection event occurred during the early stages of life's origins. Identifying structures or environments capable of inducing this selectivity is crucial for understanding the asymmetry of life.

The Potential of Fullerenes as Chiral Selection Platforms

Fullerenes, particularly C_{60} and C_{70}, can serve as platforms for molecular recognition and selective adsorption under certain conditions due to their spherical or ellipsoidal symmetrical structures, π-electron cloud distribution, and molecular hydrophilic/hydrophobic interfaces. Research indicates that in simulated primordial environments, fullerene surfaces may exhibit a preference for chiral molecules through the following mechanisms.

Induction by Asymmetric Environments

When fullerenes form complexes with metals or undergo surface grafting of organic functional groups (e.g., carboxyl, amide), asymmetric active sites emerge, exhibiting differential affinity towards D- or L-enantiomers.

Hydrophobic/π–π Stacking Differences

The stereochemical structure of D- and L-nucleotides influences their π-stacking stability with fullerene surfaces, leading to variations in adsorption energy and conformation.

Spatial Repulsion Effects

Within the "pocket" structures formed by fullerenes, molecules of differing chirality may exhibit selective binding due to distinct spatial orientations. Experimental simulations indicate that C_{60} adsorbs D-nucleotide monomers or oligomers more stably, forming robust π-stacking complexes. It may represent one of the earliest structural screening mechanisms [330].

Fullerene–Protein Complex Systems and Chiral Amplification

When fullerenes exist within a highly hydrophobic environment (such as hydrophobic native protein residues or amino acid membrane structures), their surface interactions further enhance molecular recognition effects. Simulation studies reveal that when C_{60} co-constructs microenvironments with hydrophobic amino acids (e.g., Phe, Leu, Val), it forms "cage-like pockets". This structure preferentially accommodates D-nucleotides, whose geometric conformation is better suited for alignment at the connection reaction site along the direction of the RNA chain.

This fullerene–amino acid composite system not only exhibits selective adsorption capabilities but may also function as a template-induced polymerization agent. Through non-covalent guidance, it arranges nucleotides in a specific configuration on the surface, thereby promoting the formation of a single chiral chain. This process achieves chiral amplification via an autocatalytic template-directed mechanism (+) [331].

Chiral Selection and Symmetry Breaking on Cosmic Scales

Notably, astrochemical studies indicate that amino acids in certain meteorites (e.g., the Murchison meteorite) exhibit a subtle L-form preference. At the same time, cosmic rays or circularly polarized light (CPL) may induce enantiomeric optical activity differences in specific nebular regions [332]. Should these phenomena interact with fullerene surfaces or bind to them, they may form an integrated model of chirality preference–stable binding–catalytic polymerization: CPL induces chirality isomer differences + fullerene adsorption selectivity + catalytic chain reaction → leading to the evolution of nucleotides or amino acids from enantiomeric mixtures towards a single chirality. Within this framework, fullerenes emerge not merely as inert carriers but as active inducers of life's chiral origin.

In summary, as structurally stable, surface-active carbon-rich molecules, fullerenes may exert microscopic selectivity on RNA nucleotide structure, chirality, and polymerization pathways through physical adsorption, π–π stacking, and non-covalent interactions in primordial environments. This subtle yet persistent preferential effect may represent one origin of D-ribose becoming the exclusive template in life systems. Multicomponent systems involving fullerene–metal–protein residues may provide a transitional platform from physical selection to biochemical functional evolution, offering an interdisciplinary integrated mechanism for understanding the origins of the RNA world.

Potential influence of fullerenes on RNA folding, structure, and functional evolution

As dual carriers of information storage and catalysis in early life, the three-dimensional folding capability of RNA molecules is crucial to their biological functions. The evolution from simple linear arrangements to complex functional structures—such as hairpins, G-quadruplexes, and ribozymes—represents a pivotal step in RNA's transformation from static molecules to functional machinery. Recent computational and experimental evidence suggests that carbon-rich structures such as fullerenes may play a significant "co-folding" role in RNA structural evolution. Through molecular adsorption, electrostatic interference, or spatial confinement, they induce RNA to adopt more complex and stable conformations.

Molecular Challenges and Environmental Dependence in RNA Folding

The RNA Folding Process Must Overcome the Following Difficulties

Repulsive forces between negatively charged backbones (phosphate backbone); the requirement for stable coordination of metal ions in the environment (e.g., Mg^{2++} , Fe^{2++}); spatial constraints on inter-strand hydrogen bond formation and conformational matching. In modern biological systems, these issues are resolved mainly through mechanisms such as protein chaperones and ion shielding. In primordial environments, however, fullerenes and their complexes may have naturally provided a non-enzyme-mediated "folding-facilitating platform" [333].

Mechanisms of Fullerene Action in RNA Structural Stabilization and Folding

- π–π Adsorption and Structural Support: RNA bases (particularly purines) may undergo stacking adsorption with the π-electron structure of C_{60} or C_{70}. This adsorption exhibits selectivity and can inhibit detrimental base slippage or mispairing [334]. Fullerenes may function as "molecular sandwiching agents", assisting in the maintenance of local structural stability in RNA hairpins, stems, loops, and other motifs.
- Modulation of surface charge distribution: When fullerene surfaces are loaded with metal ions or electron holes, their local potential can interfere with electrostatic repulsion between RNA backbone segments, facilitating intrastrand folding. Examples include $Fe@C_{60}^+$ or $Ni@C_{60}^+$, which create micro-regions of "electrically neutral environments" analogous to the stabilizing effect of Mg^{2++} on ribosomal RNA.
- Spatial Confinement and Template-Induced Conformation: Within confined spaces or nanoscale channels (such as those formed by multiple fullerene clusters), RNA chain folding is subject to geometric constraints, favouring the formation of stable higher-order structures, such as α-helices or G-quadruplexes. This "conformation-guided folding" enhances the probability of forming active RNA segments via non-covalent mechanisms, analogous to the conformational changes observed in modern ribozyme active sites [335].

Origin of RNA Functional Structures and Fullerene Facilitation

Under experimental conditions, RNA can self-assemble into catalytically active structures, including: Ribozymes: Catalyzing cleavage and self-ligation reactions; G-quadruplexes: Participating in ion channelling and template recognition; Hammerhead motifs: Involved in RNA cleavage reactions [336].

Experimental Simulations and Prospects of Fullerene–RNA Composite Systems

Researchers have constructed multiple RNA–fullerene hybrid systems, observing their conformational changes and reactivity under experimental conditions: RNA molecules on C_{60}-coated surfaces exhibit enhanced degradation resistance and structural stability. Within C_{60}-encapsulated nanocavities, RNA folding speed and direction become constrained, demonstrating folding pathway selectivity. UV irradiation of C_{60}–RNA complexes induces adenine monomer polymerization, demonstrating their potential as initial polymerization templates. These simulations validate the physicochemical auxiliary role of fullerene-like nanostructures in RNA functionalization, serving as a crucial bridge for understanding RNA's transition from disordered strands to ordered functional units.

In summary, fullerenes are not merely chemically inert molecular building blocks, but may be regarded as physical templates and electrochemical regulatory platforms for early RNA folding, stabilization, and functionalization. In primordial environments lacking complex biological regulatory systems, fullerenes and their metal complexes may have served as crucial non-enzymatic factors that drove RNA molecules toward functional complexity. This non-covalent regulatory mechanism may well represent the deep evolutionary memory underlying modern structures such as ribosomes and ribozymes.

The Leap from Non-Biological Proteins to Functional Components

Proteins have long been regarded as complex, functional molecules that emerged only in the later stages of life's evolution. However, recent discoveries of a novel protein—hemolithin—in carbonaceous chondrite meteorites (such as Acfer 086 and Allende) challenge this perspective [232]. Composed primarily of glycine with terminal sequences of Fe, O, Li and other elements, this protein exhibits visible light absorption and potential hydrolytic energy conversion properties, demonstrating metabolic-level functionality [233]. This discovery suggests that specific precursor functional units of proteins may have existed before the formation of RNA or genetic mechanisms, serving as crucial starting points for primordial metabolism.

Structural Characteristics and Extraterrestrial Origin of Hemolithin

Hemolithin consists of a short glycine chain, with both ends stably encapsulated by ferrocene clusters and lithium atoms, forming a unique metal-organic framework. Its recurrent presence across multiple meteorites excludes the possibility of terrestrial contamination, confirmed through mass spectrometry and high-resolution electron microscopy. Its formation environment is hypothesized to be within protoplanetary or planetary disks, requiring the following conditions: abundance of glycine precursors (Strecker synthesis under HCN+NH3 systems); presence of metallic particles (iron, lithium) and aqueous environments; sustained heat sources from radioactive isotopes (e.g.,^{26}Al); and catalytic reaction surfaces at ice-dust interfaces or within planetesimals [234].

Light-Driven Energy Release Mechanisms and Metabolic Prototypes

The ferrocentres within heme proteins possess light absorption and electron transfer capabilities, mimicking the behaviour of iron-sulphur clusters in photosynthesis. Upon exposure to ultraviolet or visible light, their ferrocentres absorb photons, triggering the following reaction:

$Fe^{2+} + h\nu \rightarrow Fe^{3+} + e^-$

$2H_2O + 4h\nu \rightarrow 4H^+ + 4e^- + O_2$

The generated electrons and protons provided raw materials for the initial energy metabolism chain, forming a primitive metabolic prototype characterized by "non-enzymatic catalysis–electro-driven–energy relay." This behaviour exhibits significant similarity to electron donor structures in modern electrotrophs, suggesting its potential as a functional module within primordial metabolic mechanisms.

Synergistic Relationship Between Dehydration Mechanisms and the RNA World

One of the most significant challenges in RNA polymerization is the inhibition of reactions by water molecules that are generated during the condensation process. The metal-terminated group of Hemolithin may function as a "molecular water scavenger", promoting phosphodiester bond formation through the following mechanism:

- Utilizing ferrocene clusters to absorb electron density, transferring or trapping water molecules in the reaction.
- Reducing water activity in aqueous environments to enhance dehydration polymerization efficiency;
- Providing an electron pathway to support excited-state intermediates in organic polymerization reactions [238,239]. This functionality positions it as a potential synergistic catalyst, bridging metabolic and genetic systems and laying the groundwork for the RNA world hypothesis.

Hemolithin and the Iron–Sulphur World Hypothesis

The iron end of Hemolithin may form structures analogous to Fe–S clusters in sulphide environments, considered the evolutionary prototype of modern metalloprotein active sites. Conditions within protoplanetary or planetary disks support this transformation: Fe/Ni/Co enrichment within disks, with S sourced from H_2S or CS_2, and the readily formed pyrite-like surface structures in hydrothermal environments [237]. Fe–S clusters possess redox potential regulation capabilities, stabilizing electron flow pathways. The emergence of Hemolithin provides a potential intermediate model for the evolutionary pathway "from non-living metal clusters to modern enzyme active sites" [235].

Summary: New Support for Metabolism-First Hypothesis

The discovery of Hemolithin and its potential functions reinforces the theoretical framework of "metabolism preceding genetics [9]." Before the development of complex RNA or DNA systems, protein-like molecules could already perform functions such as energy conversion, regulating water activity, and facilitating electron transfer. The widespread presence of this chemical structure in meteorites suggests it may serve as a cosmically universal metabolic module, playing a pivotal role in the origin of life. Future investigations into its synthetic pathways, electronic structure, and reaction characteristics will shed light on the unresolved deep mechanisms underlying the chemical origins of life.

The Completion of the Triadic Architecture of Life – Metabolism, Encapsulation, and Heredity

Hemolithin and the Origin of Primitive Metabolic Systems

The protein 'Hemolithin', first discovered in meteorite samples, has sparked widespread interest in the origins of primitive metabolic systems [232]. This protein, identified in the Acfer 086 and Allende meteorites, exhibits distinctive structural features: a short glycine-dominated peptide chain terminally coordinated with iron, lithium, and oxygen, forming a structure resembling iron oxide clusters [233]. Not only is this configuration unobserved on Earth, but its arrangement may possess potential for photocatalysis and electron transfer.

The formation mechanism of Hemolithin suggests that in protoplanetary and planetary disc environments, simple amino acids like glycine may spontaneously condense into peptides under hydrothermal and radiative conditions, subsequently binding with metallic elements in stardust. This process requires no particular catalytic conditions, supporting the "metabolism before genetics" hypothesis [234,235].

Research indicates that such metal-coordinated proteins possess triple functionality: Firstly, under intense radiation or thermal gradients, ferrocene clusters absorb photon energy to drive photolysis of water, providing a potential pathway for energy conversion in primordial environments; Secondly, the proteins themselves can adsorb small-molecule substrates via electrostatic or hydrophobic interactions, performing an enzyme-like 'pre-catalytic' function; Thirdly, their ability to exclude water molecules from their structure renders them natural platforms for promoting condensation reactions (such as nucleotide or peptide chain formation) [236,237,239].

Further analysis indicates that the presence of Hemolithin reveals conditions conducive to the formation of self-sustaining metabolic modules within protoplanets. The incorporation of lithium may relate to primordial electro-nutritional mechanisms, potentially stabilizing local charge transport or maintaining reaction centre structures.

The ferrocene cluster carried by Hemolithin may catalyze the following photoreaction process:

$Fe^{2+} + h\nu \rightarrow Fe^{3+} + e^-$

$2H_2O + 4h\nu \rightarrow 4H^+ + 4e^- + O_2$

This reaction relies on hν, i.e. high-energy photons, typically referring to ultraviolet or visible light. Such radiation can only occur in environments close to stellar illumination, such as the outer layers of protoplanetary discs or sunlit planetary surfaces. In environments such as deep-sea hydrothermal vents within the Earth or planetesimals, light cannot penetrate, rendering photocatalytic reactions impossible.

This photocatalytic process suggests that, under conditions where protoplanetary disks receive stellar radiation, Hemolithin may absorb high-energy photons, excite electron transitions, and subsequently drive water decomposition reactions [237]. It not only provides an energy source for early metabolic systems but may also establish redox gradients, creating a favourable environment for further chemical evolution.

However, within the interstellar nebula or deeper environments where stellar radiation struggles to penetrate, the aforementioned photocatalytic mechanism becomes ineffective. Here, another class of non-light-dependent energy mechanisms becomes crucial. The interstellar medium is pervaded by alpha particles, beta particles, and gamma rays released from the decay of both short-lived and long-lived radioactive isotopes (such as ^{26}Al, ^{60}Fe, ^{238}U, ^{232}Th, and ^{40}K). These high-energy particles can undergo energy coupling with organic molecules such as iron-sulphur clusters, PAHs (polycyclic aromatic hydrocarbons), and fullerenes, providing a sustained electron source for electro-nutritive microorganisms or primordial chemical systems.

For instance, alpha particles may react with iron-sulphur clusters ($\alpha + \mathrm{FeS\_cluster} \rightarrow \mathrm{Fe}^{2++} / \mathrm{Fe}^{3++} + \mathrm{e}\text{\^{}}^{-}$), whilst beta particles can excite aromatic molecules into an excited state ($\beta + \mathrm{PAHs} \rightarrow \mathrm{PAHs}^{*} + \mathrm{e}\text{\^{}}^{-}$), inducing electron transitions and releasing free electrons.

These reactions can induce charge separation and electron flow in light-free environments, constituting an “internal energy supply” mechanism analogous to modern electrotrophic bacteria (e.g., Geobacter, Shewanella). Combined with the diffusion potential of lithium or sodium ions, this may form a primitive transmembrane voltage gradient, laying the groundwork for proton pumps or electron transport chains.

Thus, even in sunlight-deprived environments, protoplanetary disks possessed multiple energy pathways supporting the evolution of primitive metabolic networks. Metal-coordinated structures, such as Hemolithin, may have served as pivotal hubs linking these energy and material flows. However, at early Earth’s submarine hydrothermal vents, the absence of significant short-lived and long-lived isotopes meant that particle-driven mechanisms similarly failed to replicate the energy conditions within protoplanetary disks. Thus, protoplanetary discs possess richer energy pathways and material conditions than the early Earth [338]. Metal coordination structures, such as hematoporphyrin, may serve as crucial molecular hubs that couple these energies to chemical evolution, providing a robust foundation for the transition from simple chemistry to primordial metabolic networks.

Before the emergence of the “RNA world,” structures like Hemolithin may have undertaken partial energy conversion and reaction-driving functions, laying the chemical groundwork for the aggregation of information molecules and potentially serving as anchoring points for membrane structures and functional complexes [9].

In summary, Hemolithin not only represents the first complete protein discovered in meteorites but is also likely one of the earliest functional biomolecules within protoplanetary discs. It reveals a continuum from simple chemistry to primitive metabolic networks, providing crucial evidence for the pathway from chemical evolution to the emergence of life.

From Metabolic Modules to the Formation of Primordial Cellular Structures

The Nature and Prerequisites for the Formation of Cellular Structures

The cell constitutes the fundamental unit of modern life systems; its emergence marks a significant transition from nonliving chemistry to living systems. Cellular structure encompasses not only semipermeable membranes and interfacial encapsulation, but also stable metabolic compartments, energy conversion mechanisms, and information transmission networks. Starting from functional modules such as Hemolithin, the evolution towards a cellular prototype requires at least the following conditions: a structure possessing spatial confinement and reaction isolation (e.g., lipid vesicles, mineral channels); the presence of sustained internal metabolic cycles (e.g., ferric-driven electron flow and water splitting); the ability to maintain ion gradients and primitive energy metabolism; and the capacity for self-expansion or stable assembly [237, 339-342].

Origin of Lipid Molecules and Protomembrane Structures

Common organic synthesis pathways in protoplanetary discs and planetesimal environments (e.g., Fischer-Tropsch reactions) can generate linear fatty acids or their derivatives. These molecules spontaneously form monolayer or bilayer membrane structures in aqueous environments. C8–C16 fatty acid chains and alcohols have been detected in meteorites; Experiments simulating interstellar ice generated amphiphilic surfactant molecules. On hydrothermal vents or alkaline mineral surfaces, lipids can adsorb and form stable membrane sheets [59,46,343]. These structures provide the interfacial foundation for embedding metabolic modules, potentially establishing the boundaries of primordial cells.

Localization Mechanisms for Metabolic Modules in Protoplasm

Metabolic modules represented by Hemolithin, when stably localized on the lipid membrane surface, can perform the following functions: forming light-harvesting complexes and proton pumps to establish ion gradients; synergizing with membrane-bound Fe–S clusters to form localized electron transport chains; facilitating transmembrane reactions and enhancing structural stability through membrane-embedded metalloproteins; and driving spatial functionalization via self-assembly of anchor-protein–membrane complexes [235,238,341,342].

The Protoplasmic Environment and Incubator for Cellular Prototype Evolution

The aqueous environment, radiothermal heating, and metallic surfaces within planetesimals provided temperature, reactive surfaces, and energy for primordial cellular precursors: 26 Al and other radioactive isotopes maintained millions of years of gentle heating within planetesimals; planetesimal mineral channels exhibited nanoscale confinement and reaction selectivity; lipid molecules could self-assemble into vesicles, encapsulating metabolic modules and generating primitive chemical homeostasis [343-345].

The Evolutionary Bridge from Hemolithin to Primitive Cells

The light-driven hydrolysis, metabolic electron transfer, and dehydration capabilities provided by Hemolithin, combined with spontaneously formed lipid vesicle structures in planetary or interstellar environments, can progressively construct primordial cells possessing the three essential elements of “metabolism–boundary–stability”: Hemolithin serve as on the primordial membrane surface, acting as metabolic catalytic nodes; electrochemical gradients form between the vesicle interior and external environment; hydrolysis products and metabolic modules maintain initial energy flow and reaction self-stability [238,341,342].

Extraterrestrial Prototypes of Cellular Structures

Cellular structures are not exclusively an Earth-specific evolutionary outcome of life. Their core mechanisms—metabolism and interface encapsulation—already existed as chemical modules within protoplanetary and planetary disks, as well as their planetesimals [59]. Hemolithin provided the atomic-level foundation for constructing metabolic networks, while lipid compounds and mineral channels offered platforms for forming spatial boundaries. Their co-evolution formed a natural bridge from nonliving systems towards a “primitive cellular state.”

Establishment of Primitive Information Systems and Selection Mechanisms in Protoplanetary Discs

Transition from Chemical Selection to Information Selection

Following the acquisition of basic information replication capabilities by the RNA system, the molecular world entered a pivotal transition phase from "physical–chemical selection" to "information–functional selection" [346]. The protoplanetary disc harbours abundant natural screening mechanisms—including temperature gradients, electric fields, variations in metal ion concentrations, and dust-membrane interfaces—providing a selective environment for the stabilization and amplification of primordial information systems [347].

Information Redundancy and Sequence Screening: How to Mitigate Noise?

High error rates and sequence redundancy frequently accompany early RNA chain polymerization under non-template conditions. However, "spatial constraints" such as mineral surfaces, charge-adsorption sites, and lipid membrane pores enhance the probability of correct base pairing [305]. Specific sequences are more readily able to form stable secondary structures (e.g., hairpin loops), thereby exhibiting higher survival rates during replication, constituting an early "structure-function" selection framework [348].

Synergistic Effects of Metal Ions and Template Chain Stability

Metal ions such as Fe^{2++} , Mg^{2++} , and Zn^{2++} can stabilize RNA structures and participate in phosphodiester bond formation. In environments containing these ions, certain RNA sequences exhibit enhanced folding capacity and replication efficiency, progressively forming a metal-dependent "sequence screening channel" that constitutes one of the early evolutionary pressures.

Spatial Realization of Selection Mechanisms: Planetesimals, Vesicles, and Interface Systems

Within the micromilieu of protoplanetary discs, the porous structures of planetesimals, vesicle boundaries, and dust interfaces may have formed "primordial reaction chambers," facilitating efficient sequence enrichment and error elimination [342]. Studies suggest that water–oil interfaces, phosphate membrane systems, or clay mineral channels could serve as in situ platforms for RNA screening and enrichment, potentially forming micro-regional triads of reaction–replication–evolution [117].

Evolutionary Trends and Functional Enhancement of Primitive Information Systems

As replication mechanisms strengthened and structures became more complex, certain RNA sequences may have acquired the following functions: acting as enzymatic catalysts (ribozymes); encoding and controlling the generation of metabolic modules; and establishing template–replication–feedback cycles, entering a phase of "evolution-driven self-enhancement ." acting as enzymatic catalysts (ribozymes); encoding and controlling the generation of metabolic modules; and establishing template–replication–feedback cycles, entering a phase of "evolution-driven self-enhancement [350]."Ultimately, these selection mechanisms guided the transition from the functionality of single RNA molecules to the primordial biological system comprising "replication units–metabolic units–membrane-enclosed compartments [351,352]."

Information Selection Mechanisms as the Core Driver of Primitive Evolution

Protoplanetary discs provided a multidimensional environment for the formation and stabilization of early RNA systems. At the same time, the establishment of information selection mechanisms signalled the actual emergence of evolutionary forces at the molecular level. This selection, grounded in both environmental screening and intrinsic stability and functional advantages, drove the fundamental leap from disordered chemistry to ordered systems [353].

Synergy between the 'lipid–information system' in protoplanetary and planetary discs and the formation of primordial cell boundaries

Sources and Formation Pathways of Lipids in the Protoplanetary and Planetary Disc Environments

Methanol, formaldehyde, acetaldehyde, and short-chain carboxylic acids—abundant in protoplanetary disks—can generate fatty acid precursors through thermochemical reactions, ultraviolet irradiation, and catalyzed surface reactions [354]. Experiments indicate that in simulated disc environments rich in CO, H_2, H_2O, and metal catalysts (such as Ni or Fe), C_8–C_{14} unsaturated fatty acids can be synthesized, providing precursor units for the formation of primordial membrane structures [355].

Assembly and Dynamic Boundaries: Mechanisms of Lipid Vesicle Formation

Fatty acids readily form monolayer or bilayer structures in aqueous phases, spontaneously closing to form membrane vesicles under temperature gradients, changes in electrolyte concentration, or pH gradients [356,357]. Within protoplanetary discs, the presence of multiple heat sources (solar irradiation, ^{26}Al decay, etc.) and mineral pore systems readily generates local osmotic and ionic gradients, thereby driving the formation and evolution of primordial lipid vesicles [358,359].

Co-evolution of Lipid Membranes and RNA Systems

Vesicles not only encapsulate RNA and metabolic molecules but also provide stable "reaction chambers" that prevent molecular diffusion. Notably, the incorporation of metal cations (such as Ca^{2++} or Mg^{2++}) into phospholipid or fatty acid membranes [360]enhances RNA strand stability and polymerization efficiency [360,361]. Transmembrane ion gradients formed across the membrane also provide the driving force for RNA replication or energy transfer (e.g., proton gradient-driven processes) [362].

Functionalization and Selectivity of Primitive Cell Boundaries

As membrane structures became more complex and functionally enhanced, certain vesicles evolved the following characteristics: heightened semipermeability (selective ion or molecular permeability); incorporation of simple channel proteins or metal-polymer structures; and support for metabolic flux and energy conservation. These "proto-cellular" boundary systems, possessing rudimentary functions, became platforms for information selection and metabolic integration, exhibiting sustained evolutionary and competitive advantages [363].

Membrane Systems as Key Hubs for Information-Metabolic Coupling in Protoplanetary and Planetary Discs

Lipid structures not only provide physical boundaries but also serve as coordinators between metabolic and informational systems. The exothermic, molecule-rich, and metal-abundant environment of the protoplanetary disc enabled the co-evolution of the "lipid–RNA–metabolism" triad, laying the foundation for the formation of primordial cellular structures [364].

Integration of Energy, Protein Metabolism, and Membrane–Genetic Systems in the Protoplanetary Disk

Multiple Energy Sources: Key Drivers of Molecular System Integration

Protoplanetary disks harbour not only solar radiation (infrared, ultraviolet, and X-rays) and heat/alpha/beta particles from radioactive isotope decay (e.g., ^{26}Al, ^{60}Fe, ^{238}U, ^{232}Th, and ^{40}K), but also local hydrothermal reaction systems within the protoplanetary disk. These energy sources construct multi-level energy distribution and conversion pathways, supporting catalytic reactions within primordial metabolic modules and sustaining the energy of the membrane system [343].

Proteins and Peptide Chains: The Bridge Between Metabolism and Membrane Function

Inspired by primordial proteins such as hematite proteins, small peptide chains (e.g., glycine oligomers) found in meteorites are proposed as mediators of early metabolic functions [365]. These peptide chains could bind to membrane systems to form primitive channels or act as co-catalysts, stabilizing metabolic reaction chains and creating environmental advantages for the amplification of RNA or lipid structures [366].

Chimeric Evolution of Lipid–Protein Complexes and Information Systems

Within the asteroid environment, characterized by frequent temperature fluctuations and variations in ionic concentration, peptide chains embedded in membrane vesicles form stable complexes. These structures enhanced the selective permeability of vesicles and even supported primitive proton pump mechanisms [305]. Concurrently, RNA chains achieved stable replication within these structures. The information, metabolic, and energy systems are progressively integrated through a “membrane–protein–RNA” cooperative network [34].

System Encapsulation: From Modular Assembly to Dynamic Steady-State Systems

Within stardust or dust aggregates, lipid vesicles encapsulating metabolic molecules and informational polymers gradually evolved into primordial systems possessing the tripartite functions of “replication–metabolism–boundary” [367]. Metal ions and transition metal catalysts facilitated reaction rates while enhancing structural stability, serving as catalytic frameworks for system integration [359].

Synergistic Networks Establish a Homeostatic Platform for Primitive Life Systems

Within the high-energy, element-rich environment of the protoplanetary and planetary disks, the integrated evolution of energy-driven processes, protein-assisted mechanisms, membrane-structured protection, and information systems constitutes the prelude to primordial life systems [346]. Metabolism and information ceased to be isolated modules, instead achieving mutual aid within membrane boundaries, thereby progressively evolving towards the highly organized protoplasmic precursor.

Evolutionary Selection and Environmental Adaptation of Life Systems: Synergistic Co-evolution from Nebula to Planetary Body

The Chemical Legacy of Nebulae and the Life Foundation of Protoplanetary Discs

The Solar System’s precursor was an interstellar nebula rich in carbon, nitrogen, oxygen, and metals, which formed a protoplanetary disc through gravitational collapse [368]. Organic molecules already present in the nebular phase (e.g., HCN, CH_4, H_2CO, PAHs) underwent further polymerization, catalysis, and selective evolution within the disc, providing material and structural templates for prebiotic systems [15,369].

The Planetary Body Interior: Sanctuary for Primordial Systems

As planetesimals gradually coalesce within protoplanetary discs, their interiors develop a closed, warm environment due to the decay of radioactive isotopes such as ^{26}Al, ^{60}Fe, ^{238}U, ^{232}Th, and ^{40}K [370]. This environment not only sustains liquid water but also activates a series of critical reactions, including amino acid synthesis, peptide chain polymerization, and RNA replication, forming a “proto-cell factory” where metabolic and informational systems operate in closed, synergistic coordination [371,372].

Selective Pressure and System Stability: From Dispersion to Integration

Primitive metabolic units encountered stresses such as radiation, high temperatures, and dehydration in complex environments. Systems possessing membrane structures, energy regulation mechanisms, and information replication functions demonstrated superior adaptability to these challenges. Through local resource optimization, error elimination, and molecular repair mechanisms, these systems gradually stabilized, giving rise to “primordial ecological selection [370].”

Long-Term Energy and Ecological Maintenance Mechanisms

Beyond initial isotopic energy inputs, stars continuously supply energy in the form of infrared and visible light, sustaining surface temperatures and energy fluxes on planetesimals. Some early systems may have evolved electro-nutritional mechanisms, utilizing electron flows generated at rock–water–metal interfaces to maintain metabolism, such as primordial electron transport systems assisted by hematite proteins [373].

Nutrient Cycling and Protosystemic Embryos

Within protoplanets, small primordial biological systems with electron metabolism could sustain their own energy cycles by decomposing complex molecules or through environmental reduction reactions [29]. Cooperative-competitive relationships between different functional modules gradually formed primitive ecological structures, establishing the microscopic foundation for protoplanets to sustain life systems over extended periods [374].

Evolutionary Continuity from Nebular Chemistry to Planetary Ecosystems

Life systems are not a singular emergent phenomenon unique to Earth, but rather complex systems continuously shaped and selected through the progression from nebulae to protoplanetary discs to planetesimals. The matter, energy, and dynamic structures within protoplanetary discs not only catalyze the origin of life but also construct the fundamental framework for its adaptation and evolution [375].

The Protoplanetary Disk and Planetary Disk: Universality and Prospects for Extraterrestrial Life Detection?

Universality of Protoplanetary Disk Conditions

Modern astronomical observations indicate that protoplanetary disks (PPDs), rich in dust and gas, are ubiquitous around sun-like stars [16]. These disks exhibit striking similarities to the early Solar System in terms of chemical composition, temperature gradients, radiation environments, and metallicity, suggesting that fundamental environments conducive to life may be widespread throughout the Milky Way and beyond [160].

Universal Synthesis Pathways for Amino Acids and Prebiotic Chemistry

Carbonaceous chondrite meteorites (such as Allende and Acfer 086) provide evidence that Strecker synthesis reactions and PAH-induced mechanisms can proceed within the alternating low-temperature, radiation, and hydrothermal conditions of protoplanetary disks, synthesizing diverse nitrogen-containing organics and amino acids [124,376]. These pathways are independent of Earth’s unique conditions, rendering them feasible within protoplanetary disks across other galaxies.

Interstellar Evolutionary Potential of Planetary Ecosystems

As revealed by haematite protein, metal-containing small peptide structures can maintain electron flow and metabolic prototypes within protoplanetary disks [377,324]. Should such structures repeatedly form across other star systems, they could constitute "interstellar protosystems". Particularly, stony meteorites bearing radioactive nuclides (such as ^{26}Al and ^{40}K) possess the conditions to maintain temperature, drive metabolism, and construct membrane structures, becoming fundamental units for the propagation and reconstruction of interstellar life systems [378]. Whilst the concept of an "interstellar primordial ecosystem" is theoretically discussable, considering the temporal scale of interstellar exchange and the environment of intense cosmic radiation, I do not believe the conclusion above is viable.

Detection Prospects: From Spectral Lines to Meteorite Analysis

Future continuous observations of outer-disk molecular spectral lines (e.g., HCN, CH_3CN, PAHs) and dust dynamics, via telescopes such as ALMA and JWST, combined with in-situ sampling and analysis of meteorites, comets, and interstellar dust, will further validate whether analogous prebiotic synthesis conditions and products exist [379,130].

Universality and Predictability of Cosmic Life

Protoplanetary discs harbour not only universal pathways for the synthesis of prebiotic precursors, but also multi-level systems of nested energy maintenance, material encapsulation, and information replication mechanisms, indicating that life's origin possesses "conditionally replicable" properties [380]. Should these formation mechanisms prove universal, extraterrestrial life may similarly follow integrated chemical-structural-systemic pathways, exhibiting predictable characteristics and identifiable signatures.

From Local Origins to Cosmic Universality

Protoplanetary and planetary discs are not merely the starting point for life on Earth, but also a crucial window for understanding the universality of life across the cosmos. By integrating astronomical observations, experimental simulations, and meteorite evidence, humanity is progressively mapping a trans-temporal and trans-spatial chemical blueprint for life, providing both theoretical foundations and detection pathways for the discovery of extraterrestrial life.

Chiral Induction and Mechanisms of Information Symmetry Breaking in Protoplanetary Disks

The asymmetric distribution of matter and high-energy environments within protoplanetary and planetary discs provides a crucial backdrop for early-stage chiral selection in life. The detection of D-enantiomer-rich amino acids in carbonaceous chondrites (e.g., Acfer 086, Allende) indicates that this chiral bias did not originate from terrestrial biological processes but was established during the disc's evolutionary phase [381].

Circularly polarized ultraviolet (UV-CPL) light scattered from the interstellar medium or young stars can induce chiral selection in amino acids or nucleotides [382]. For instance, experiments demonstrate that glycine, valine, and other amino acids exhibit 5%–20% enantiomeric bias under circularly polarized light [383]. Furthermore, aromatic-rich structures formed by polycyclic aromatic hydrocarbons (PAHs) and metallic dust can create "chiral pockets". These selectively bind D-form nucleotides via π–π stacking and steric hindrance, serving as primary templates for the unidirectional polymerization of information chains [384].

Against this backdrop, the early information systems of life were not merely neutral chemical chain combinations, but rather the selective superposition resulting from the concerted effects of physically induced, catalytically active environments and molecular structures. Chiral bias not only influences protein folding but also determines the directionality and replication fidelity of RNA chains, thereby progressively establishing "information asymmetry" and "selective pressure" at the molecular level [385].

Factors within protoplanetary discs—such as ultraviolet radiation intensity, mineral-organic composite structures, magnetic fields, and charged particle flows—interact to form a systemic chiral induction network [386]. It is upon this foundation that informational functions transitioned from the physical preferences of monomeric structures to the macroscopic logic of genetic coding.

Thus, chiral bias is not a subsequent event but is deeply embedded within nebular and protoplanetary disc chemistry. Its emergence represents a crucial leap towards the evolution of ordered complex systems in life and may constitute one of the most significant chemical signatures in the search for extraterrestrial life.

The Origin of Genetic Replication Mechanisms and the Evolution of Fidelity

Proteins, as functional biomolecules, serve roles far beyond energy storage and structural components within life systems. Their folded states determine catalytic activity, binding specificity, and signal transduction functions. The origin of protein function, particularly in abiotic environments like protoplanetary discs, has long been regarded as a critical bottleneck in the chemical evolution of life.

Hemolithin, discovered in carbonaceous chondrite meteorites (such as Acfer 086 and Allende), provides a breakthrough clue. These micro-peptides are rich in glycine and feature terminal modifications with iron, lithium, and oxygen atom clusters, exhibiting distinct folded conformations and metal-assisted stabilized structures. It demonstrates that small protein structures with cooperative stabilization mechanisms can form in cell-free environments [387].

The abundance of amino acids in protoplanetary discs—particularly hydrophobic and aromatic types—combined with metal ions (Fe^{2++} , Ni^{2++} , etc.) and mineral surfaces, constructs a "folding template"-like environment. Clay minerals (e.g., montmorillonite) and metal sulphides (e.g., pyrite) can assist linear peptide chains in adopting regular spatial conformations through electrostatic and coordination interactions [388]. Moreover, the "layer-by-layer folding–selective retention" mechanism, driven by wet-dry cycles and thermal gradients, may also constitute a significant force in the early conformational evolution of proteins [389].

In terms of functionalization, the variable residues and steric hindrance of protein molecules create a microenvironment that facilitates primordial catalytic activity. Simulation experiments indicate that short-chain peptides can exhibit peroxidase-like, metallo-reductase, or proton-transfer activity, particularly when bound to metal ions [390]. These "functional prototypes" of proteins serve as a bridge for the subsequent emergence of RNA–protein cooperative systems.

In summary, protein folding and functionalization did not commence after the origin of life. Still, they may have been deeply embedded within the diverse and complex environments of protoplanetary and planetary discs, representing a crucial manifestation of the self-organizing capacity of prebiotic molecular systems.

Synergistic Homeostatic Mechanisms of Membrane–Genetic Systems

Throughout the stages of life's origin, the differentiation of membrane structures and genetic mechanisms did not occur independently. Instead, they co-evolved through a series of interdependent and synergistic feedback mechanisms. Membranes served not merely as physical compartments but as the core regulators of boundary conditions and energy gradients for chemical reactions within prebiotic systems. Conversely, genetic systems relied on the spatial stability of membrane structures to maintain molecular recognition, replication, and catalysis.

Protoplanetary discs already exhibited environments where lipid precursor molecules (e.g., fatty acids, aldehydes, isoprenoids) coexisted with RNA precursors (e.g., nucleotides, oligonucleotides). Simulation experiments demonstrate that simple fatty acids can spontaneously form monolayer vesicles under condensation or wet-dry cycling conditions, forming complexes with RNA molecules. These complexes further stabilize the membrane structure and enhance its selective permeability [391].

Conversely, the formation of lipid membranes also facilitated the selective replication of genetic molecules. For instance, vesicular structures could enhance replication efficiency and prevent product diffusion by encapsulating specific template strands and replicase precursors. This mechanism provided the foundational framework for the subsequent emergence of "cell-like" units of life [392].

Moreover, membrane structures sustain proton-driven mechanisms via cation gradients, enabling the operation of early molecular motors or energy-converting enzymes. Genetic molecules, in turn, stably express their catalytic functions under these electrochemical conditions. A synergistic homeostasis gradually emerges: membranes provide spatial constraints and energy support for replication systems, while protein products from genetic systems optimize membrane synthesis and maintenance [393].

This mutually dependent evolutionary mechanism demonstrates that life did not originate from a single mechanism. Instead, the triad of metabolism, membrane, and genetics progressively formed a stable system through symbiotic coupling within protoplanetary and planetary discs. This system, embedded with homeostasis, represents not only the starting point of the "primitive cell" but also the lowest threshold at which natural selection can act. It is crucial to emphasize that metabolism preceded both membrane and genetics.

Dynamic Steady State and Self-Replicating Cycles in Protoplanetary Disk Life Systems

The persistence of life systems relies not only on the construction of material structures but also on their capacity for dynamic homeostasis, which maintains their own structure and function. Within the complex environment of the protoplanetary disc, the precursor life systems formed there must simultaneously possess three capabilities: the acquisition and distribution of metabolic energy, the continuous regeneration of structure and function, and the stable transmission and feedback of information.

This system, termed the "self-maintaining and self-replicating cycle," constitutes not a simple linear reaction chain but a dynamic network. Its core components include the regenerative mechanism of primordial metabolic units, where hemolithin and other metallopeptides catalyze dehydration reactions and energy transfer processes. Once anchored to the surfaces of planetesimals, a mineral-photon energy drive can sustain their cyclical operation [394]. Dynamic synthesis and reconstruction of the lipid–membrane system: Membrane components undergo periodic renewal through alternating wet and dry cycles and thermal gradients, whilst self-assembling with nucleotide or small peptide assistance to form dynamically adjustable boundary structures [395]. Cyclic reconstruction of the RNA–protein interaction module: Short-chain RNA collaborates with primordial peptides to construct prototypical ribosomal functions, perpetuating structural module information and functional characteristics through template recognition mechanisms [396].

The emergence of such dynamic steady-state systems signifies a transition from "chemical systems" to "biological systems." The key lies not in the complexity of individual molecules but in the self-organization, self-repair, and feedback regulation capabilities of the holistic network. From heat sources in protoplanetary discs (such as ^{26}Al decay and solar radiation) to mineral active centres within planetesimals, and against the backdrop of extreme wet-dry cycles in geostellar-orbital rhythms, all provide support for the formation of such cyclic networks.

Thus, a hypothesis may be proposed: the "prototype life systems" within protoplanetary discs are not accidental occurrences, but rather the inevitable outcome of multiple feedback mechanisms. These systems ultimately evolve into stable structures that possess replication and mutation capabilities, thereby providing the foundational groundwork for subsequent natural selection and Darwinian evolution.

From the Birth of Life in the Protoplanetary Disk to the Evolution of Life within Planetary Disk Planetesimals

The protoplanetary disc of the Solar System inherited a rich metallicity, particularly isotopes of metals and heavy metals with varying half-lives. It provides more reliable support for theories concerning the origin of life within the protoplanetary disc and planetary discs. Isotopes with both short and long half-lives not only sustain the ongoing activity of Earth's core and mantle, forming the fundamental source of the planet's magnetic field, but more significantly, they may constitute the very basis for theories positing the origin of life within the protoplanetary disc. Indeed, without these isotopes, life on Earth might not exist. They not only facilitated the synthesis of prebiotic chemistry, including amino acids, nucleobases, and peptides, within the protoplanetary disc but also laid the essential groundwork for life's metabolism, the formation of cell membranes, and the establishment of the genetic triad. Based on the comprehensive prebiotic analysis presented herein, primordial cells had already formed by the late stages of the protoplanetary disc. However, establishing the cell's entire metabolic network—including diverse proteins and their enzymes, the emergence of the RNA world, and the transition from RNA to the more stable DNA-based hereditary system—required protracted processes. It encompassed the development of DNA polymerase, the transcription system that converts DNA into RNA, and its associated transcriptases. Crucially, the establishment of the modern protein translation system demanded further extensive evolutionary time. This process may have required hundreds of millions, or even billions, of years. Under what environmental conditions could a life metabolic network, resembling that of modern archaea and bacteria, have emerged with a stable and sustained energy supply? I contend that only the protoplanetary disc around the Sun, and subsequently the planetesimal discs, possessed the stable internal environment and continuous, reliable energy source required. This energy source derives not only from the Sun's thermal radiation, solar and cosmic electromagnetic waves, and other radiations, but more significantly from the atomic energy and various molecules produced by the radioactive decay of short- and long-half-life isotopes within protoplanetary bodies. These molecules share a direct lineage with the gaseous molecules present in the protoplanetary disc. This further substantiates the theoretical self-consistency of the hypothesis that life originated within the protoplanetary disc.

Below, I shall return to the solar system's protoplanetary disc and systematically re-examine how life gradually emerged within it, and how it subsequently evolved within the planetary bodies of the later solar system. These metabolic pathways and networks could only have been realized within the protoplanetary disc and its successor planetary bodies. Without the unique elemental composition of the solar system's protoplanetary nebula, particularly its isotopic signature, life on Earth might never have arisen.

Revisiting the Paradoxes of Earth's Life Origin Theories

The protoplanetary disc primarily comprised reducing gases such as H_2, CO, H_2O, CH_4, and NH_3, alongside abundant PAHs, HCN, CH_3OH, and CH_3NH_2. These molecules are highlighted explicitly because they were virtually absent from the ancient Earth's atmosphere. Contemporary research indicates that the Earth's atmosphere during the Archaean Eon was dominated by CO_2 and N_2, with extremely low concentrations of CO, hydrogen, and methane, resulting in an overall neutral to oxidizing environment. Within such conditions, the classical Miller-Urey reaction (which relies on potent reducing gases like CH_4 and NH_3) proved highly inefficient. Even later, extended Miller-Urey experiments sought to replicate conditions across different zones of the protoplanetary disc—such as the inner disc, middle disc, snow line, and outer disc. Consequently, to date, no practical experiment or archaeological evidence exists that demonstrates the generation of prebiotic chemicals—such as amino acids, nucleic acid bases, or fatty acids—on the primordial Earth.

The emergence and evolution of life occurred over hundreds of millions of years within the protoplanetary and planetary discs, culminating in the archaea, bacteria, and eukaryotes we observe today. The prevailing school of thought on Earth's origin posits that life arose near volcanic or deep-sea hydrothermal vents; this dominant theory suggests life originated around deep-sea black smokers. However, I shall not elaborate here on the water paradox, which renders amino acid polymerization and nucleic acid condensation in water highly unfavourable. Constructing life's comprehensive metabolic networks and genetic systems requires hundreds of millions of years of stable environmental conditions and continuous energy supply. Moreover, the integrated chemical reactions involved are extraordinarily complex, combining physics, chemistry, quantum physics, quantum chemistry, and quantum biology into a series of intricate, interconnected reaction networks. The survival capabilities exhibited by Earth's current lifeforms are unlikely to have emerged solely from hydrothermal vents. It is particularly true during Earth's early history, when the crust was volatile and tectonic activity was intense. Volcanic eruption sites were constantly shifting. Simultaneously, the locations of hydrothermal vents on the seafloor were also in flux, with the majority confined to mid-ocean ridges and submarine mountain ranges [397]. Whether volcanic or hydrothermal, such activity could only persist for millions, at most tens of millions, of years. Yet, life's evolution requires hundreds of millions, if not billions, of years. Life can't emerge and subsequently evolve at the exact location over hundreds of millions of years [398].

Whether it is volcanic eruptions, hydrothermal vents, or even lightning, their energy supply is profoundly unstable, characterized by immense randomness and discontinuity, much like our current inability to predict precisely when or where an earthquake will strike. Thus, lightning, volcanoes, and hydrothermal vents are intermittent rather than regular (with the notable exception of Old Faithful). Volcanic and hydrothermal activity is influenced by tectonic plate movements, particularly on the primordial Earth, where such activity was vastly more vigorous than it is today. This single thermal energy source for life's origin falls far short of explaining the complexity of life's energy requirements. Even reports suggesting hydrothermal vents generate redox potential differences via F-S reactions to provide electrical power must account for the inherent instability and discontinuity of such possible differences and thermal energy production. The theory of life's origin on Earth also presents paradoxes regarding the continuity and stability of energy.

As discussed earlier, the prebiotic chemical reactions required diverse chemical processes. Many such reactions could not occur on Earth at all. It applies to both the primordial materials required for these reactions and the physical and chemical conditions necessary for their occurrence. The materials for these reactions—including the primordial gases needed to synthesize prebiotic substances like amino acids in the Miller-Urey experiment- did not exist on Earth. Furthermore, the hydrogen (H_2) and carbon monoxide (CO) required for the habitat of the Last Universal Common Ancestor (LUCA) were also absent on our planet [399]. Even within deep-sea hydrothermal environments, LUCA would have required hundreds of millions of years of gradual evolution to complete the full life cycle, from primitive metabolism to a complete metabolic network, culminating in a fully functional metabolic and genetic system. Therefore, none of the processes from prebiotic synthesis to LUCA could have been accomplished on Earth [238]. So where did life on Earth originate?

From the Protoplanetary Disc to the Interior of Planetesimals: A Continuum of Environmental Consistency

As analyzed in the previous chapter, neither the atmospheric conditions required for amino acid synthesis on early primordial Earth (as demonstrated by the Miller–Urey experiment) nor the H_2 and CO_2 environment needed for LUCA at hydrothermal vents on the ocean floor existed on Earth. Moreover, reactions ranging from Fischer–Tropsch-type synthesis ($CO + H_2 \rightarrow$ hydrocarbons + H_2O) to the Haber-type synthesis ($N_2 + H_2 \rightarrow NH_3$) – which produce precursor materials for amino acids, nucleobases, and fatty acids – were fundamentally unfeasible under the natural conditions of the primordial Earth. The primordial Earth fundamentally lacked the hydrogen (H_2) and carbon monoxide (CO) required for these reactions, nor did it possess the necessary Fe/Co/Ni catalysts, which functioned as dust-like agents in the reactions. Such conditions were simply unattainable in the terrestrial environment. Only within the protoplanetary disc could these processes occur. It further demonstrates that, beyond the aforementioned gases and reaction conditions, the prerequisites for prebiotic chemistry could not have been fulfilled on the primordial Earth. Polycyclic aromatic hydrocarbons (PAHs) and fullerenes, crucial prebiotic substances, were present in the protoplanetary disc at concentrations exceeding those on the primordial Earth by over one hundred million times.

These compounds also serve as precursors for amino acids, nucleobases, and fatty acids. It provides further evidence of the impossibility of Earth's environment generating the precursors for life. The Strecker synthesis reaction, a prototypical pathway for amino acid synthesis, has demonstrated its reactivity and raw material requirements within the protoplanetary disc. On Earth, however, this reaction remains confined to laboratory test tubes. No evidence exists to suggest that the ancient Earth completed the reactions mentioned above.

The gas and molecular environment of the protoplanetary disc—H_2O, CO, H_2O, CH_4, NH_3, along with abundant PAHs, HCN, and electrons—provides the essential life-sustaining environment and materials for life within the planet. Notably, these elements also constitute the environment, nutrients, and energy sources upon which LUCA (the Last Universal Common Ancestor) is believed to have depended: H_2, CO, H_2O, CH_4, NH_3, and electrons. Such life, originating within the protoplanetary disc and planetary bodies, along with its continuous metabolic environment and the nutritional and energy requirements it demands, cannot be sustained solely by deep-sea hydrothermal vents. Instead, it relies upon the stable internal environment provided by the protoplanetary disc and subsequently by the planetary bodies themselves. This internal environment not only receives radiation and energy from solar radiation but also harnesses energy from both short- and long-half-life radioactive elements within the planetesimal, along with the physical, chemical, quantum physical, quantum chemical, and quantum biological reactions induced by their radioactive decay. It is precisely this continuity—spanning hundreds of millions, even billions of years—of stable, consistent chemical molecules, reaction conditions, and energy supply within the protoplanetary disc and subsequently within the planetesimal interior of the planetary disc that constitutes the fundamental basis for the emergence and sustained, stable evolution of life. This process of life's origin and evolution within protoplanetary and planetary discs fundamentally differs from Earth's conditions for life's emergence, which relied upon sporadic volcanic activity and hydrothermal vents triggered by tectonic plate movements. Therefore, we must assert that the origin of life constitutes a comprehensive, quantifiable, repeatable, and verifiable process spanning billions of years. It encompasses physical, chemical, and quantum mechanical factors, observable and discoverable through current solar system archaeology and the study of protoplanetary discs. The origin of life is not a fanciful, accidental, fortuitous, sudden, or instantaneous event—a process that may be simulated in laboratories yet remains self-contradictory. Below, I shall elaborate on the entire process of life's origin and evolution, from the protoplanetary disc of the solar system to the planetesimal within the planetary disc. It will chart the complete chain and pattern from life's origin, through the formation and evolution of protocells, to the Universal Ancestral Common Organism (LUCA) with its full metabolic and genetic networks. This pattern is only achievable by leveraging the billions, even tens of billions, of years provided as pivotal timeframes by short- and long-half-life radioactive isotopes. These factors are absent in studies of the origin of life on Earth, yet they constitute the fundamental determinants of life's origin.

Wherever Gases and Molecules Exist, Life Ought to Emerge There: Philosophical Self-Consistency

Life did not begin 'from scratch' on Earth, but commenced its chemical evolution—and even early forms—within cosmic 'incubators' such as protoplanetary discs, planetesimals, and comets. Earth merely provided a suitable environment for a highly evolved pre-life system to continue developing and flourishing.

Legitimate Challenges to the Traditional Earth-Centred Model: The Conventional "Primordial Soup" Theory Faces Significant Difficulties

Speculation in the Beaker

Experiments like the Miller-Urey reaction did indeed synthesize amino acids in simulated atmospheres. However, the actual composition of the early Earth's atmosphere remains highly contentious to this day (was it reducing, neutral, or oxidizing?). Many of the molecules produced would have been extremely unstable under the intense ultraviolet radiation, high temperatures, and acidic oceanic conditions of the primordial Earth, making it difficult for them to accumulate to concentrations sufficient for effective reactions.

The Absence of Evidence

Earth's active geological processes have virtually obliterated all chemical traces from 4 billion years ago. We find no direct, uncontested chemical evidence of the "moment of life's origin" in Earth's oldest rocks. It leaves a vast gap.

Abundance in Interstellar and Protoplanetary Discs

We now know that the interstellar medium, comets, and meteorites are replete with prebiotic compounds. Over 10,000 organic molecules have been identified in carbonaceous chondrite meteorites (such as Murchison), including protein amino acids, nucleic acid bases (purines, pyrimidines), fatty acids, and sugar derivatives. Their diversity and complexity far exceed any Earth-based simulation experiments. It is no longer conjecture, but an observational fact.

Painting a Picture of Cosmic Origins: Life Taking Root in Planetesimals

The precursor chemical reactions for life can readily occur within the cosmic environment, rich in raw materials. Thus, a new picture unfolds:

The Stage of Life

Protoplanetary Disc & Planetesimals Abundant Raw Materials

The protoplanetary disc, a by-product of stellar formation, is rich in H_2, CO, CO_2, H_2O, CH_3OH, NH_3, HCN, along with PAHs and silicate dust [400]. These molecules adsorb onto dust particle surfaces, forming icy mantles. Energy Sources: Intense ultraviolet radiation from the protostar, radioactive decay, shock waves from particle collisions, and geothermal heat (within larger planetesimals) provide sustained energy. Ideal 'microreactors': Porous planetesimals: These tens to hundreds of metres in size possess porous interiors, offering vast surface areas for chemical reactions. Coexistence of water and organics: Radioactive decay generates sufficient heat to melt ice, forming liquid water inclusions. It creates a 'meteorite hydrothermal system' – a perfect reaction vessel encapsulating water (the universal solvent) and complex organics. Mineral catalysis: Abundant iron-sulphur minerals (e.g., pyrite, magnetite) and clay minerals provided excellent catalytic surfaces, facilitating the fixation and polymerization of molecules like CO and HCN into more complex structures (primitive forms akin to iron-sulphur clusters and metal-PAH complexes).

The Process of Life

From Chemical Evolution to the "Seed of Life", within this cosmic cradle, chemical reactions ceased to be random. Synthesis and Screening: Over millions of years, synthetic reactions persisted within liquid water inclusions, yielding abundant amino acids, lipids, and nucleotides. Confinement within micropores elevated concentrations, while selective adsorption on mineral surfaces (e.g., certain clays preferentially adsorb right-handed amino acids or specific bases) facilitated abiotic selection and enrichment [401].

Assembly and Replication

Lipids spontaneously formed membrane vesicles, encapsulating these organic molecules to create protocells [402]. Certain RNA-like molecules may have exploited mineral surface catalysis to achieve initial, inefficient self-replication. It was not yet life, but rather constituted highly complex "prebiotic chemistries." Primitive Metabolism: These systems may have evolved rudimentary pathways utilizing readily available environmental molecules (e.g., H_2, CO). For instance, a protocell vesicle encapsulating Fe-S minerals and Ni might mimic the most primitive hydrogenase function, reducing H^+ to H_2 while releasing energy. It represents the cosmic prototype of metabolic pathways.

The Relationship between "Seed" and "Garden"

Earth is the garden, not the workshop. Under this model, the "workshops" for the origin of life on Earth were asteroids and cometary nuclei scattered throughout the solar system. During its late formation phase, Earth endured the Late Heavy Bombardment, a period of intense asteroid and Kuiper belt activity that lasted hundreds of millions of years. Seeding: Countless such planetesimal fragments (meteorites) and comets scattered these highly evolved life forms—including diverse bacterial seeds—across the early Earth, much like sowing seeds [403].

Prosperity

The early Earth possessed vast oceans and stable energy sources (geothermal heat, sunlight). Bacteria within these planetesimals, having remained inside them for a period, gradually adapted to Earth's milder, more persistent environment. These "cosmic visitors" found an exceptionally favourable "garden" where they rapidly progressed from initial adaptation upon arrival to flourishing development. LUCA (Last Universal Common Ancestor) could also have originated within planetesimal bodies within the planetary disc, rather than on Earth itself.

Addressing the Ultimate Question

Must the gases and molecules required for bacterial life originate in environments devoid of these substances on Earth? Absolutely not.

The chemical foundations of life most likely emerged within an environment already saturated with these gases and molecules. While such molecules may have existed in Earth's primordial state, the cosmic environment (within protoplanetary disks) offered a superior, more stable, and enduring reaction setting. Stability: The interior of protoplanetary bodies shielded fragile organic molecules from the destructive effects of cosmic radiation and extreme temperature fluctuations. Concentration: The microporous structure naturally concentrated reactants, a feat difficult to achieve in the early Earth's oceans. Timescale: The chemical evolution within protoplanetary discs and protoplanetary bodies could persist for tens of millions to hundreds of millions of years, affording ample time for complex trial-and-error processes.

Conclusion

The origin of life represents a cosmochemical process, with Earth serving as both inheritor and thriving habitat of its outcomes, though not necessarily its sole birthplace. It does not negate evolutionary theory but instead expands the stage for life's emergence from Earth's oceans to encompass the entire Solar System. Although no direct evidence of living bacteria has yet been found in meteorites (their prolonged space travel and violent re-entry make survival improbable), the discovery of highly complex chemical precursors suggests a possible direction. Future missions may seek evidence that this "cosmic cradle" remains active in the subsurface oceans of Mars, Enceladus, or Europa.

The "radiation-metabolism coupling hypothesis" of life's origin and the "radiation-metabolism coevolution" hypothesis

The "radiation-metabolism coupling" hypothesis for the origin of life

Gases and molecules within the protoplanetary disc of the Solar System are highly coupled with gases within planetesimals in the planetary disc. It effectively forms a remarkably complete chain of protoplanetary disc–planetesimal–proto-cell–metabolic evolution, exhibiting logical coherence with the Wood–Ljungdahl pathway ( ), radiochemical products, and antioxidant/radiation resistance adaptations [404].

Within the minuscule planetesimals formed in the early protoplanetary disc, the decay of both short-lived and long-lived radioactive isotopes (such as ^{26}Al, ^{60}Fe, ^{238}U, and ^{232}Th) generates alpha, beta, and gamma particles, as well as secondary electrons [24]. These high-energy particles, bombarding water, CO_2, and carbon-bearing minerals within the planetesimal, generated heat while also producing H_2, CO, CH_4, electrons, and other small molecular gases via radiolysis and reduction reactions [405,406]. Primitive chemotrophic autotrophs (including early methanogens and acetogens), utilizing H_2 and CO as primary energy and carbon sources, employ the Wood–Ljungdahl pathway to reduce CO_2 and CO into acetyl-CoA, achieving highly efficient carbon fixation [407]. Concurrently, radiation by-products such as hydroxyl radicals ($\cdot OH$) and hydrogen peroxide (H_2O_2) possess potent oxidative properties, causing damage to cell membranes, proteins, and nucleic acids and prompting hydrogen- and carbon-dependent microorganisms to evolve robust antioxidant defence systems early on (e.g., catalase, superoxide dismutase, and Fe–S cluster repair mechanisms) [408]. They also developed radiation resistance under persistent cosmic background radiation [409].

Fortunately, these protocells, having emerged within the protoplanetary disc, could directly utilize the disc's abundant gases (H_2, CO, CH_4, NH_3, and H_2O vapour) for metabolism. However, approximately 10 million years into the disc's evolution, these gases were progressively scattered by solar wind-driven outflow towards the outer disc and even the Oort Cloud region, leaving planetesimals as the primary reservoir sustaining metabolic processes. At this stage, radioactive isotopes within the planetesimal continuously bombard Fe–S clusters, PAHs, water, and carbon-bearing minerals, generating a steady stream of H_2, CO, CH_4, and free electrons. This process provides an uninterrupted supply of energy and material foundations for diverse microbial metabolic types. This environment drove the diversification and adaptive enhancement of life forms within planetesimals over hundreds of millions of years, enabling protoplasts to gradually differentiate into diverse bacterial and archaeal species with distinct metabolic pathways and ecological niches. This process demonstrates that the metabolic evolution of early solar system life was closely coupled with radiochemical processes within the protoplanetary disc-planetesimal system [410].

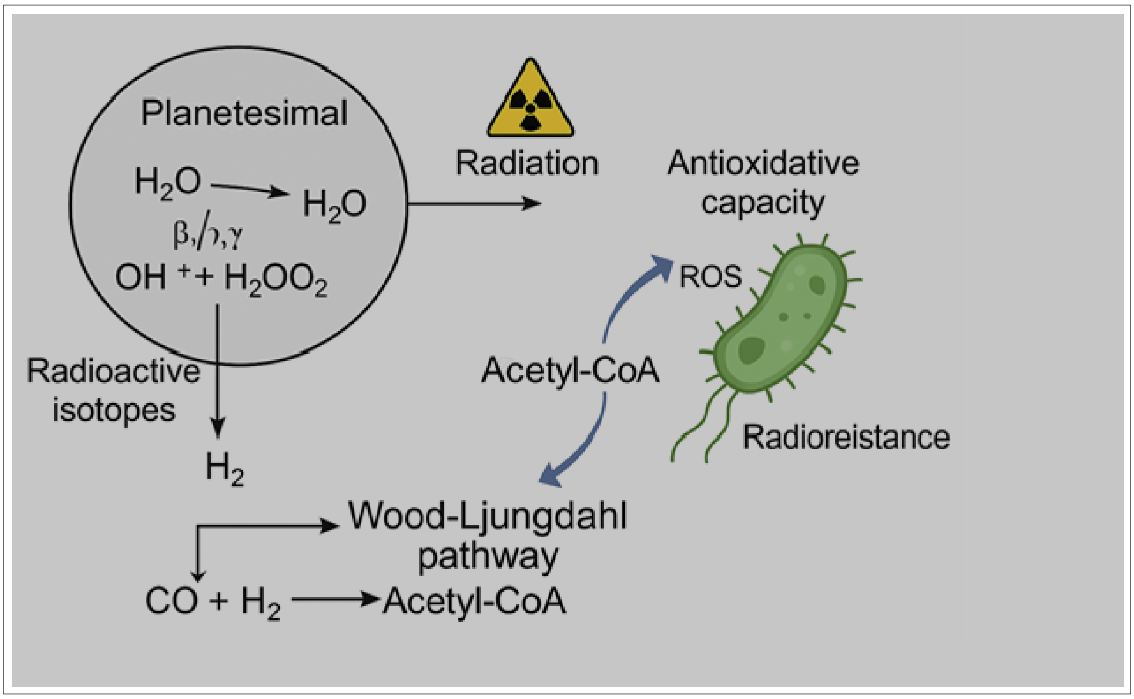

Figure 2: Mechanistic flowchart illustrating the transition from planetary body radiochemistry to microbial metabolic and resistance evolution, depicting the relationships between H_2, CO supply chains, ROS generation, radiation sources, and the Wood–Ljungdahl pathway.

The 'radiation-metabolism coupling' hypothesis regarding which radioactive isotopes in the solar system protoplanetary disc may have supported life's origin and evolution:
Summary table of key long- and short-lived radioisotopes in protoplanetary discs and their radiolysis effects on planetesimal materials, including half-lives, decay modes, radiation types, and products upon bombardment of common substances (H_2O, C-O bonds, F-S clusters, PAHs):

Summary Table of Protoplanetary Disk Radioisotopes and Their Radiolysis Effects

Isotope	Half-life	Decay Mode	Radiation type	Bombardment of H_2O products	Bombardment C-O/organic compounds products	Bombardment of F-S clusters/ PAHs products
^{26}Al	717,000 years	β-$^{+}$ e (82%), electron capture (18%)	e^{+}, γ (1.809 MeV)	H_2, H_2O_2, OH·, e-$^{-}$, aqueous	CO, CH_4, carboxylic acids	$^{+}$F e^{2+}/Fe^{3+}, thiols (-SH)
^{60}Fe	2.6 million years	β^{-}	e^{-}, γ (1.173 MeV)	H_2, H_2O_2 (low yield)	Alkanes (C_2-C_4)	FeS nanoparticles, H_2S
^{40}K	1.25 billion years	β-$^{-}$ s (89%), EC (11%)	e^{-}, γ (1.46 MeV)	H_2 (slow), OH·	trace CO	K^{+} embedded in layered silicate
^{238}U	4.47 billion years	α, SF (spontaneous fission)	α (4.27 MeV)	H_2, H_2O_2 (high LET)	Aromatic ring cleavage (e.g., benzene→ phenol)	UO_2^{2+}, SO_4^{2-}
^{232}Th	14 billion years	α	α (4.01 MeV)	Similar to ^{238}U, but with lower yield	Similar to ^{238}U	ThO_2, sulphur oxides
^{146}Sm	103 million years	α	α (2.53 MeV)	H_2 (low efficiency)	Not apparent	Sm^{3+} Reduction $S^{2-} \rightarrow S_n^{2-}$
^{53}Mn	3.7 million years	EC	X-rays, Auger e^{-}	H_2 (indirect), OH· (minor)	Mn^{2+} -catalysed CO→formic acid	MnS cluster, disulphide (S_2^{-})
^{107}Pd	6.5 million years	β^{-}	e^{-}, γ (0.214 MeV)	H_2 (trace amount)	Pd nanoparticles catalyse CH_4 formation	PdS, thio-carboxylic acid

^{10}Be	1.39 million years	β^-	e^-, γ (none)	H_2 (minor)	^{10}B embedded in organic phase (rare)	BeO, silicates
^{36}Cl	301,000 years	β-$^-$, EC	e^-, γ (1.142 MeV)	HCl, OH·	Chlorinated hydrocarbons (e.g. CH_3Cl)	$FeCl_2$, Sulphochlorides
^{41}Ca	99,000 years	EC	X-rays	$Ca(OH)_2$ colloid	No direct effect	CaS, sulphate

The table above presents commonly used and well-documented radiogenic nuclides from the early Solar System, covering the most critical nuclides for planetary thermal history and early chemical discussions.

Environmental Significance of Key Isotopes

Short-lived nuclides (^{26}Al, ^{60}Fe): Dominated early (<5 million years) heating, driving planetoid melting and differentiation. ^{26}Al's γ-rays penetrate ice layers, triggering deep-water radiolysis [316,24]. Long-lived nuclides (^{238}U, ^{40}K): Sustain long-term (□1 billion years) subterranean hydrothermal systems, supporting deep biospheres [143,259]. Transition-metal nuclides (^{53}Mn, ^{107}Pd): Catalyze organic synthesis (e.g., Fischer-Tropsch reaction), promoting prebiotic chemistry.

Geological and Experimental Evidence: Meteorite Record

The presence of ^{60}Ni, a decay product of ^{60}Fe, in Allende meteorites confirms its primordial existence [316]. Experimental simulation: α-irradiation of the H_2O+FeS system produces H_2 and Fe^{3++} [411].

Regarding "Products from Bombarding Different Targets

H_2O (liquid/ice): e^- _aq, H·, ·OH, H_3O^+, H_2, H_2O_2; O_2, $HO_2\cdot/O_2$ observable in high-dose/mixed conditions$^-$. These constitute the elementary product spectrum under all ionizing radiation (α, β, γ, and secondary electrons) [412].

C–O systems (CO/CO_2 with $H_2O/CH_4/CH_3OH$ ice mixtures): HCO, H_2CO, HCOOH, CH_3OH, CH_4, CO_2 (mutually convertible), and more complex organics; products strongly influenced by composition and temperature [313].

Fe–S (pyrite/FeS/biogenic sulphide clusters): ·OH, H_2O_2-induced $Fe^{2++} \rightarrow Fe^{3++}$, S(0)/polysulphide anions, surface radicals and electron transfer; under anoxic conditions, photolysis products may drive "anoxic pyrite oxidation" and ROS generation [413].

PAHs: Ionization (PAH^+ /PAH^-), dehydrogenation/rehydrogenation, fragmentation (commonly Cn^+ carbon clusters and small hydrocarbon fragments), configurational isomerization and surface effects (low-energy surfaces, high-energy bulk); concurrently occurring with cosmic ray/ion irradiation and VUV/UV photochemical reactions [414].

Mixed ice (H_2O: CO/CO_2:CH_4:NH_3, etc.): Cosmic ray/heavy ion irradiation leads to the destruction and resynthesis of precursor molecules, with observed formation of H_2CO, H_2O_2, CH_4, HCOOH, etc., accompanied by sputtering/desorption.

From the above List, we can Essentially Discern that all Gases and Molecules Present in the Protoplanetary Disc

H_2 (hydrogen), CO (carbon monoxide), H_2O (water vapour), CH_4(methane), NH_3 (ammonia)—along with abundant PAHs (polycyclic aromatic hydrocarbons), HCN (hydrocyanic acid), and electrons, are also generated within the planetesimal fragments of the disc. It occurs due to heat production from the decay of radioactive isotopes and radiolysis [260]. The same gases and molecules previously present in the protoplanetary disc are also retained within the planetary disc planetesimals. These gases and molecules, which can be produced and retained within the planetary disc planetesimals, include H_2, CO, H_2O, CH_4, NH_3, along with abundant PAHs, HCN, and electrons. So, what is their relationship to the bacteria we observe today?

Below, molecules/gases/electrons are listed in two columns: "Who requires/utilizes it" and "Who produces it", with representative archaeal/bacterial names provided (aiming for balanced coverage of both archaea and bacteria). A list of key metal enzymes and "electrophagous" microorganisms is appended, along with a note on the localization of metal–PAH complexes to avoid confusion with modern metabolism.

H_2 (Hydrogen)

Who uses it (Electron Donor/Energy Source)

Archaea Methanococcus maripaludis, Methanobrevibacter smithii, Methanobacterium formicicum (methanogens using $H_2 + CO_2 \rightarrow \rightarrow CH_4$); Bacteria: Desulfovibrio vulgaris (sulphate reduction, using H_2 as donor), Acetobacterium woodii (acetogenic bacteria, $H_2 + CO_2$ carbon fixation), Hydrogenobacter thermophilus [415].

Who Produces (Metabolic End-Product)

Bacteria: Clostridium butyricum, Clostridium acetobutylicum (fermentation produces H_2), Enterobacter aerogenes (also known as Klebsiella aerogenes, FHL system), Rhodopseudomonas palustris (photofermentation/nitrogen fixation by-product H_2). Archaea: A few thermophilic archaea release H_2 under specific conditions (small quantities, typically consumed) [416].

Key Enzymes

[NiFe]/[FeFe] hydrogenase; ferredoxin mediates low-potential electron transfer.

CO (Carbon Monoxide)

Who Utilizes (Carbon/Electron Source)

Bacteria: Oligotropha carboxidovorans (CO oxidation), Carboxydothermus hydrogenoformans ($CO \rightarrow H_2 + CO_2$), *Moorella thermoacetica, Acetobacterium woodii* (acetogenic bacteria capable of utilizing CO); Archaea: *Methanosarcina acetivorans* (can utilize CO under specific conditions) [417].

Producers

Bacteria (trace/signalling or bypass): Haem oxygenase releases CO (e.g., *Staphylococcus aureus* IsdG/I, *Mycobacterium tuberculosis* MhuD); non-biological sources (pyrolysis/photochemistry) are more prevalent; most microbes primarily consume CO.

Key Enzymes

CODH/ACS (Ni–Fe–S), core of the Wood–Ljungdahl (acetyl-CoA) pathway [417,148].

H_2O (Water)

Who Utilizes It

Bacteria (oxygenic photosynthesis using H_2O as electron donor):

Synechocystis sp. PCC 6803, Prochlorococcus marinus; Universal (solvent/substrate), applicable to both archaea and bacteria.

Producers
Reduce O_2 to H_2O at the terminal stage of aerobic respiration: e.g., *Escherichia coli, Bacillus subtilis, Pseudomonas putida*; also in archaea such as Sulfolobus solfataricus (aerobic archaeon).

Key Enzyme
Cytochrome oxidase (complex IV, Cu/Fe).

CH_4 (Methane)
Who Utilizes (Methanotrophic Oxidation)
Bacteria (methanotrophs): *Methylococcus capsulatus (Bath), Methylosinus trichosporium OB3b, Methylomicrobium album*; Archaea (anaerobic methane oxidation, AOM): *"Candidatus Methanoperedens nitroreducens*" (ANME-2d), *"Candidatus Methanophagales"* (ANME-1; often co-metabolizing with sulphate reducers) [419,420].

Who produces (Methanogenesis)
Archaea (sole biosynthetic producers of CH_4): *Methanobacterium formicicum, Methanobrevibacter smithii, Methanococcus maripaludis, Methanosarcina barkeri, Methanothrix soehngenii (formerly Methanosaeta)* [421].

Key Enzymes
Final step of methanogenesis, MCR (cofactor F_{430}–Ni); methane oxidation to methanol catalyzed by pMMO (Cu) or sMMO (dife iron) (note: MMO is not a Ni enzyme) [422,423].

NH_3/NH_4^+ (Ammonia/Ammonium)
Who Utilizes It
Universal nitrogen assimilation: Escherichia coli, Bacillus subtilis, most archaea/bacteria via GS–GOGAT assimilation; NH_3 as an energy substrate (ammonia oxidation): AOB *Nitrosomonas europaea* (bacteria), AOA *Nitrosopumilus maritimus* (archaea) [424].

Who Produces
Nitrogen fixation yielding NH_3: *Azotobacter vinelandii, Klebsiella pneumoniae, Rhizobium leguminosarum* (symbiotic with legumes); Deamination/urease yielding NH_3: P*roteus mirabilis, Helicobacter pylori* (urease with high nickel content); DNRA (dissociative reduction of nitrate to ammonium): e.g. *Shewanella oneidensis* [425].

Key Enzymes
GS–GOGAT (assimilation), AMO/HAO (ammonia→ hydroxylamine→ nitrite), urease (Ni) [426].

PAHs (Polycyclic Aromatic Hydrocarbons)
Who Utilizes them (Degraded as Carbon Sources)
Bacteria: *Pseudomonas putida, Sphingobium yanoikuyae (Sphingobacterium genus), Mycobacterium vanbaalenii PYR-1, Rhodococcus jostii RHA1;* Fungi also excel (for reference): Phanerochaete chrysosporium.

Producers
Direct biological "PAH synthesis" is rare; natural/anthropogenic pyrogenesis, as well as photochemistry, are more common. Modern cells do not utilize environmental PAHs as universal electron carriers, distinguished from "quinones" (see below).

Key Enzymes
Aromatic dioxygenase/monooxygenase (Fe/non-haem iron)

HCN/CN^-
Who Utilizes (Assimilation/Detoxification)
Bacteria: *Pseudomonas pseudoalcaligenes CECT 5344* (can utilize CN^- as nitrogen source under alkaline conditions), *Rhodococcus rhodochrous* (nitrocyanase family, broad-spectrum degradation of cyanide/cyanide-containing compounds); Archaea: Rarely observed (often sensitive to CN^-).

Producers
Bacteria (secondary metabolism/antagonism): *Pseudomonas aeruginosa* (hcnABC), *Pseudomonas fluorescens, Chromobacterium violaceum*.

Key Enzymes
Nitrilase/nitrile hydratase; HCN synthase (hcnABC).

Electrons (e^-) and Electron-Eating/Electron-Producing (EET) Microorganisms
Electron efflux (electrode/mineral as acceptor, electricity production/external respiration): Bacteria: Geobacter sulfurreducens, *Geobacter metallireducens, Shewanella oneidensis MR-1, Desulfuromonas acetoxidans* [427].

Electron-accepting (Electrode/Mineral as Donor, Electron-Consuming/Electroautotrophic/Electrosynthetic)
Bacteria: *Sporomusa ovata* (electrosynthetic acetate production, CO_2 fixation), *Clostridium ljungdahlii* (microbial electrosynthesis), "*Candidatus Tenderia electrophaga*" (marine cathode autotrophy), *Rhodopseudomonas palustris* TIE-1 (photoelectroautotrophy); Archaea: *Methanococcus maripaludis, Methanosarcina barkeri* (electromethanogenesis, capable of direct/indirect electron uptake from cathodes) [428,429].

Relevant Complexes/Components
Ome-cytochrome complex (Omc/Mtr), conductive pili/outer membrane nanowires; iron-sulphur clusters serving as low-potential electron "relay stations".

CO_2 (carbon dioxide)
Who Utilizes (Archaea/Bacteria) Carbon fixation (Calvin cycle, rTCA, 3-HP, Wood–Ljungdahl, etc.) Cyanobacteria
Prochlorococcus marinus, Synechococcus; Sulphur/iron/hydrogen autotrophs: Thiobacillus denitrificans, Hydrogenobacter thermophilus, Nitrobacter/Nitrospira; Acetobacter/methanogens: Acetobacterium woodii, Methanopyrus kandleri
Sources: (Archaea/Bacteria) TCA/decarboxylation, fermentation by-products, widespread respiration/fermentation.

Key enzymes
Enzymes for CO_2 fixation

This forms the core of carbon skeleton construction. (Key enzymes for CO_2 fixation: The Calvin Cycle includes Ribulose-1,5-Bisphosphate Carboxylase/Oxygenase (Rubisco), Function
Catalyzes the first and most critical step of the Calvin cycle [430]. It combines one molecule of CO_2 with one molecule of ribulose-1,5-bisphosphate (RuBP) to produce two molecules of 3-phosphoglycerate (3-PGA), thereby converting inorganic carbon (CO_2) into organic carbon [431]. Significance: This represents the primary entry point for carbon into the biosphere on Earth. For bacteria, it serves as the starting point for synthesizing all cellular carbon skeletons.

Phosphoribulokinase (PRK), Function

Catalyzes the final regeneration step of the Calvin cycle, using ATP to phosphorylate ribulose-5-phosphate (Ru5P), thereby regenerating the CO_2 acceptor – ribulose-1,5-bisphosphate (RuBP). Importance: Ensures the CO_2 fixation cycle can proceed continuously.

Enzymes utilizing inorganic substances to obtain energy and reducing power: These are pivotal for supplying the CO_2 fixation process with its driving force (ATP) and "reducing power" (NADPH).

Various specific oxidases

Cytochromes and quinone electron carriers. Function

Electrons generated by the oxidases mentioned above enter the electron transport chain (ETC) located in the cell membrane, where they are transferred through a series of carriers (such as quinones, the cytochrome bc_1 complex, and cytochrome c). Core function: During electron transfer, protons (H^+) are pumped across the cell membrane, establishing a transmembrane proton gradient (chemical osmotic potential) [432].

ATP Synthase, Function

Utilizes the generated proton gradient to drive ATP synthesis. It represents the direct pathway for chemolithotrophic bacteria to produce ATP.

Reverse Electron Transport

This resolves the "reducing power (NADPH)" issue. Problem

The electron potential obtained from oxidizing inorganic compounds (e.g., H_2S) is often insufficiently low (insufficiently negative) to directly reduce NAD^+ (requiring low-potential electrons). Solution: Bacteria consume part of the energy from the proton gradient to forcibly drive electrons "upstream", transferring them in reverse from carriers with higher potential to carriers with lower potential (e.g., NAD^+), thereby reducing it to NADH. Key Enzyme: This process is accomplished by a complex enzyme system involving NADH: quinone oxidoreductase (complex I), utilizing the proton motive force to reverse electron transfer from quinone (QH_2) to NAD^+.

O_2 (oxygen)

Who Utilizes It

(Archaea/Bacteria) Terminal electron acceptor (cytochrome oxidase), widespread in aerobic heterotrophs/autotrophs; cyanobacteria also require O_2 respiration (dark phase) for autotrophy.

Producers: (Archaea/Bacteria) Oxygenic photosynthesis (oxygen release via PSII water splitting) Cyanobacteria: Prochlorococcus marinus, Synechococcus sp., Anabaena sp.; (later) algal chloroplasts.

Key Enzymes

Bacterial oxygen utilization and oxygen production involve entirely distinct enzyme systems distributed across different bacterial groups.

Key Enzymes for Bacterial Oxygen Production

Within the bacterial domain, only one group can produce oxygen: cyanobacteria (Cyanobacteria). They accomplished Earth's greatest biochemical revolution—the invention of oxygenic photosynthesis [433].

At its core lies a complex protein-metal complex rather than a single enzyme: the oxygen-evolving complex (OEC) [434].

Location

Embedded within Photosystem II (PSII), situated on the thylakoid membrane.

Core Structure

Its active site comprises a unique manganese-calcium-oxygen cluster (Mn_4CaO_5), also termed the "manganese cluster" [435]. This inorganic metal cluster ranks among nature's most potent biological oxidation catalysts [436].

Function

Catalyzing the water-splitting reaction. $2H_2O \rightarrow O_2 + 4H^+ + 4e^{--}$

Mechanism

Photosystem II absorbs light energy, generating high-energy electrons. This energy drives the manganese cluster through a cyclic sequence of oxidation states (S_0 to S_4). Upon accumulating four quanta of light (undergoing four oxidation steps), the manganese cluster (in the S_4 state) possesses sufficient oxidative capacity to extract four electrons from two water molecules. This process simultaneously produces four protons (H^+) and one oxygen molecule (O_2), with oxygen being released as a metabolic waste product [435].

Significance

This represents the sole biological structure in nature capable of efficiently and sustainably catalyzing water splitting. Its emergence directly precipitated the Great Oxygenation Event (GOE), fundamentally transforming Earth's landscape [433].

Key Enzymes for Bacterial OXYGEN utilization

The vast majority of oxygen-utilizing bacteria do not produce oxygen themselves; they utilize oxygen present in their environment. These enzymes are primarily categorized into two major groups:

Enzymes for Energy Metabolism (Respiratory Chain)

These are terminal oxidases located at the end of the respiratory chain, responsible for transferring electrons to oxygen to complete aerobic respiration [437]. Including: Cytochrome c oxidase; Cytochrome bd oxidase; Cytochrome cbb_3 oxidase [438,439].

Enzymes for Biosynthesis and Degradation

Which do not generate energy but utilize oxygen as a substrate to catalyze various chemical reactions [440]. These include: oxygenases; oxidases (non-respiratory chain, typically producing H_2O_2) [441].

Key Metal Enzymes/Cofactors and their Relationship with Transition Metals in Protoplanetary Discs and their Planetary Disc Planets

- **Fe–S cluster proteins (e.g., ferredoxin):** Universal electron transfer; capable of self-assembling in situ to form "prototype" clusters under Fe^{2++} +H_2S conditions.
- **Hydrogenases ([NiFe]/[FeFe]):** H^{+} □ H_2, reversibly regulating H_2 "consumption" and "production" [415].
- **Nitrogenase (FeMo/FeV/FeFe):** $N_2 \rightarrow NH_3$ (ATP-consuming), O_2-sensitive [442].
- **Cobalamin (vitamin B_{12}):** Co^{1+} $/^{2+}$ $/^{3+}$ participates in methyl transfer/rearrangement via reversible valence states (widespread in archaea and bacteria; eukaryotes often acquire it from microorganisms).
- **Cu enzymes:** cytochrome oxidase (O_2 terminal reduction → H_2O); pMMO is a Cu enzyme (methane→ → methanol)

[443].
- **Biferric enzymes:** sMMO (methane→ → methanol, no copper requirement) [443].
- **Zn enzymes:** carbonic anhydrase, zinc metalloproteases (Note: DNA polymerase catalytic centres primarily utilize Mg^{2++}; Zn typically serves structural/regulatory roles).

Regarding Metal–Small Molecule/Metal–PAH Complexes (Prebiotic/Material Chemistry Positioning)

- **Feasible mechanisms (prebiotic/materials chemistry):** Fe–PAH, Si–PAH, Ti–C_{60}, transition metal carbide/nitride nanoclusters, FeO clusters, etc., capable of electron transfer under light/ionization/surface interactions or catalyzing CO_2 reduction and small molecule generation (H_2/HCN/HCOOH).
- **Positioning in Modern Biology:** These are not standard intracellular metabolic enzymes or essential cofactors; life has adopted quinones (ubiquitin/menadione/methanophenazine) as universal membrane-bound electron carriers, biosynthesized endogenously within cells rather than derived from environmental PAHs.
- **Bridging perspective:** Fe–S clusters and Ni/Co centres (B_{12}, CODH/ACS, MCR, etc.) suggest evolutionary continuity at the "metal–organic" interface; metal–PAH systems more closely resemble potential prebiotic catalytic templates/reaction platforms.

PAH Oxidation Products (Quinones) and Electron Transfer Potential

Under illumination, ionization, or oxidative conditions PAHs may form "quinone" structures under conditions of light exposure, ionization, or oxidation, such as naphthoquinone and benzoquinone. These molecules possess the following biochemical significance: Highly efficient electron acceptors: Quinone molecules may participate in single- or double-electron transfer; Formation of electrochemical gradients: When coordinated with Fe^{2++} / Fe^{3++} or other metals, they may generate primordial electron currents; Precursor function: In modern organisms, quinones (such as ubiquinone and coenzyme Q) serve as pivotal electron carriers in respiratory and photosynthetic chains [191].

Consequently, the oxidative derivatives of PAHs formed within protoplanetary discs may have laid the groundwork for early primordial metabolic networks. Given that PAH concentrations in protoplanetary discs exceed those on ancient Earth by a factor of one hundred million to one billion, ancient Earth's PAH levels were negligible. Thus, leveraging the electron transfer potential of PAH oxidation products (quinones), subsequent chapters shall elucidate the origin of octopus-like organisms and the relationship between their metabolic systems and quinones—particularly the intimate connection with ubiquinone (UQ). Concurrently, we shall emphasize the critical link between quinones such as plastoquinone (PQ) and the Great Oxygenation Event (GOE).

The "Radiation-Metabolism Coevolution" Model of Life's Origin

Within the interior of minuscule planetesimals formed in the early protoplanetary disc, decay products (α, β, γ particles) of both short-lived and long-lived radioactive isotopes (e.g., ^{26}Al, ^{60}Fe, ^{238}U, ^{232}Th, ^{40}K) could bombard water, CO_2, sulphur-containing/iron-bearing minerals, and polycyclic aromatic hydrocarbons (PAHs) within the planetesimal. Through photolysis and reduction reactions, these processes continuously generate H_2, CO, CH_4, free electrons (xml-ph-0000@deepl.internal), and other molecules. Iron-bearing minerals and polycyclic aromatic hydrocarbons (PAHs). Through radiolysis and reduction reactions, these processes continuously generated H_2, CO, CH_4, free electrons, and other small molecular gases [287]. These products supplied energy and carbon sources for protocells and early chemotrophic autotrophic microorganisms, particularly methanogens and acetogens, relying on the Wood–Ljungdahl pathway to convert CO_2/CO into acetyl-CoA [405,236]. However, the radiolysis process simultaneously generates highly oxidative by-products such as hydroxyl radicals (·OH) and hydrogen peroxide (H_2O_2), accompanied by high background radiation. It poses a persistent threat to cellular proteins, nucleic acids, and membrane structures. Under this dual environmental stress, H_2 and CO-dependent microorganisms must have evolved robust antioxidant systems (e.g., catalase, superoxide dismutase, Fe–S cluster repair enzymes) and radiation resistance [317]. This adaptation likely arose not only from radiochemical selection pressures within protoplanetary disks but also from combined exposure to solar wind and galactic cosmic rays [444]. As the protoplanetary disc gradually dispersed its gaseous components into the outer disc or Oort Cloud via solar wind erosion over approximately 10 million years, radiochemical processes within planetesimals became the primary energy source sustaining microbial metabolism. This enabled primordial cells to diversify over hundreds of millions of years into distinct bacterial and archaeal lineages exhibiting diverse metabolic types and pronounced resistance characteristics.

The "Radiation-Environment-Metabolism Co-Evolution" Hypothesis

Antioxidant Capacity of H_2/CO Utilizing Microorganisms

These microorganisms universally possess potent antioxidant capabilities because their primary energy-producing environment (radioactive radiolysis within protostars) is simultaneously a high-yield source of reactive oxygen species (ROS). It compelled them to develop sophisticated ROS scavenging and repair mechanisms during early evolutionary stages [445].

Radiochemical Causality

This antioxidant capacity is not incidental but a direct outcome of the planetary radiation-chemical environment. Radioisotopes simultaneously supply the reducing gases (H_2, CO) essential for metabolism while generating oxidative by-products that degrade biomolecules, thereby evolutionarily coupling antioxidant defences with energy metabolism [446].

Co-evolution of Radiation Resistanc

Subjected to prolonged exposure to multiple radiation stresses from both internal and external sources (radioisotope decay + solar wind + cosmic rays), the antioxidant systems of these microorganisms co-evolved with DNA/protein repair mechanisms. Consequently, they exhibit remarkable radiation resistance to this day [447].

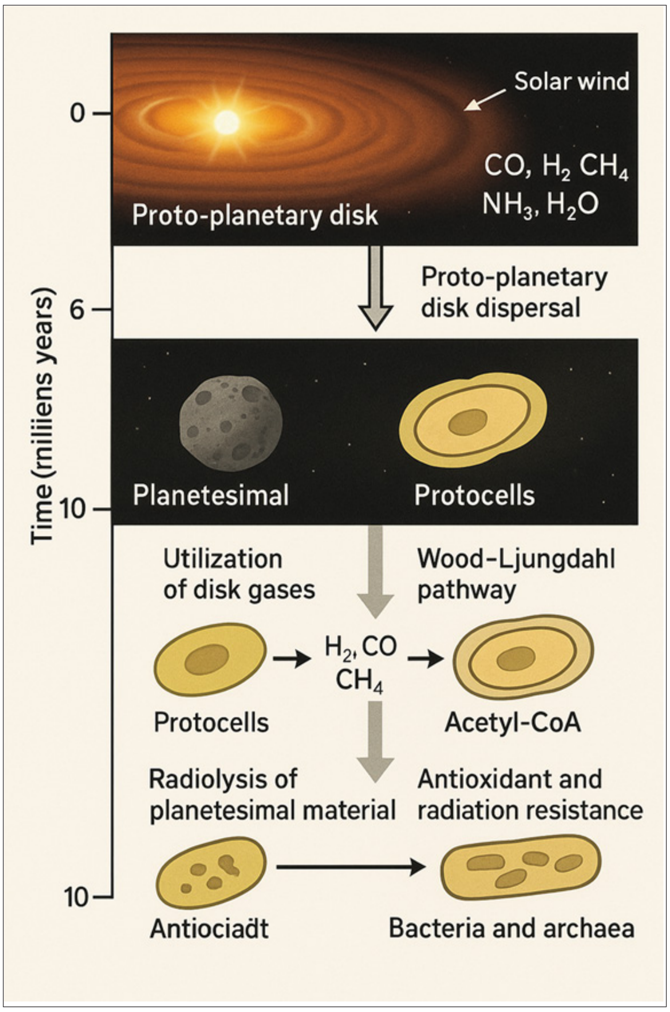

Figure 3: Timeline and Metabolic Adaptive Evolution Diagram: “Protoplanetary Disk Gas-Rich Phase →Disk Gas Scattering → Radiation Chemistry Within Planetesimals Sustaining Metabolism → Metabolic Differentiation and Resistance Evolution”

Through the above narrative and analysis, we observe that primordial cells originating in the protoplanetary disc could evolve within planetesimals. Exposed to cosmic rays and the heat generated by isotope decay within these bodies, alongside molecules produced by radiolysis, these primordial cells developed into archaea and bacteria exhibiting distinct metabolic characteristics. Numerous bacteria are situated at the root of LUCA [399]. These bacteria possess distinct metabolic networks and modes of inheritance [448]. Yet after undergoing billions of years of evolution within protoplanetary disc pebbles, the systems they developed for DNA replication, transcription from DNA to RNA, and translation from RNA to proteins became consistent. What principle, then, approximately guided the establishment of the protein translation code?

Evidence of high radioisotope abundance in meteorites and models for the origin of life (radiation–metabolism coupling and co-evolution) Radioisotopic Characteristics in the Murchison Meteorite

Carbonaceous chondrites (such as Murchison, CM2 type) indeed preserve radioactive isotopes and their decay products in concentrations exceeding the ‘average’ values found in Earth’s crust, providing crucial evidence for studying the early solar system’s radioactive environment [449]. Compared to modern Earth crust, the Murchison meteorite preserves substantial quantities of decay products from both short-lived radioactive isotopes (SLRs) and long-lived radioactive isotopes (LLRs) [450]. Short-lived radioactive isotopes (SLRs). These isotopes have almost entirely decayed on Earth today. Yet, their daughter-product anomalies persist within meteorite minerals (pyroxene, olivine, silicate inclusions), demonstrating the existence of a strongly radiologically driven chemical background during the solar system’s formation.

Short-lived isotopes (SLRs)

Decay products of ^{26}Al, ^{60}Fe, ^{53}Mn, and ^{129}I are distinctly recorded in meteorites [451]. Their initial abundances in meteorites are markedly higher than in Earth’s crust, as they preserve traces of supernova and stellar nucleosynthesis injections during the solar system’s infancy (<10 Myr) [452]. Following Earth’s formation, 4.5 billion years of radioactive decay have nearly entirely depleted these short-lived isotopes. Meteorites, however, serve as ‘frozen samples’ that preserve the radioactive fingerprints of the early solar nebula.

Compared to the radioactive element content of Earth’s modern crust, the Mochison meteorite preserves substantial quantities of decay products from short-lived radioactive isotopes (SLRs):

- ^{26}Al → ^{26}Mg (half-life 0.7 Myr)
- ^{60}Fe → ^{60}Ni (half-life 2.6 million years)
- ^{53}Mn → ^{53}Cr (half-life 3.7 Myr)
- ^{129}I → ^{129}Xe (half-life 16 Myr)

These isotopes have almost entirely decayed on Earth today. Yet, their daughter anomalies persist within meteorite minerals (pyroxene, olivine, silicate inclusions), demonstrating the existence of a strongly radiologically driven chemical background during the formation of the Solar System.

The long-lived radioactive isotopes (LLRs, such as ^{238}U, ^{232}Th, ^{40}K, ^{87}Rb, etc.) preserved in the Mochison meteorite exhibit abundances markedly different from the crustal average.
Like other carbonaceous chondrites, the Mochison meteorite contains long-lived radionuclides and their decay products similar to those found on Earth:

o ^{238}U → ^{206}Pb (half-life 4.47 Gyr)
o ^{235}U → ^{207}Pb (half-life 0.70 Gyr)
o ^{232}Th → ^{208}Pb (half-life 14 Gyr)
o ^{40}K → ^{40}Ar / ^{40}Ca (half-life 1.25 Gyr)
o ^{87}Rb → ^{87}Sr (half-life 48.8 Gyr)
o ^{147}Sm → ^{143}Nd (half-life 106 Gyr)

The Mochison meteorite and terrestrial materials also contain significant quantities of long-lived radioactive isotopes (LLRs). These isotopes, with half-lives in the range of 10^8–10^{10} years, persist to the present day and constitute a crucial source for long-term planetary internal heating and radiochemical processes. Overall, the abundances of these elements in meteorite samples are typically higher than the modern crustal average, yet closely match the chemical composition of the mantle and the Earth as a whole [259]. This discrepancy stems from planetary differentiation: during Earth’s formation, stony elements like uranium, thorium, and potassium underwent redistribution between the mantle, crust, and core. Subsequent magmatic differentiation and plate cycling diluted their average concentrations in the crust.

In contrast, Mochison meteorites, as primordial planetesimals that avoided extensive melting, preserve the original composition of the solar nebula. The coexistence of these LLRs with short-lived nuclide products in Mochison meteorites indicates their fixation into solids during nebular condensation and the early protoplanetary disc phase. They not only supplied energy for meteorite heating and organic chemistry but also provided a persistent background for long-term radiometabolic environments.

The Radioactive Environment and Chemical Evolution of the Protoplanetary Disc

The radiative environment within the protoplanetary disc was far more intense than that of the modern crust. The presence of SLRs (particularly ^{26}Al, half-life 0.7 Myr) indicates a highly potent radiative energy source within the early disc. These radioactive isotopes heated the interiors of planetesimals, triggering water-rock reactions and hydrothermal chemistry. Radiation energy is intrinsically linked to chemical evolution. The Mochison meteorite not only preserves records of short-lived nuclides (^{26}Al, ^{60}Fe, ^{53}Mn, ^{129}I) but also contains long-lived nuclides (^{238}U, ^{232}Th, ^{40}K, ^{87}Rb, ^{147}Sm), releasing not only heat but also radiation (β, γ, secondary particles). This radiation could drive the decomposition and resynthesis of CO_2, H_2O, NH_3, and HCN. The organic compounds found in the Mochisen meteorite, such as amino acids and nucleoside precursors, are likely linked to this radiochemical background [453]. Earth's Radiation Legacy Earth formed within the same radiation-rich nebular environment, though short-lived nuclides subsequently decayed. Thus, the radiation-metabolism pathways utilized by early life can be traced back to the protoplanetary disc-planetesimal environment, rather than Earth itself.

Planetesimal heating and differentiation: Rising internal temperatures triggered ice-rock reactions and hydrothermal convection, providing conditions for complex organic synthesis. Radiation-induced chemical reactions: Irradiation of CO_2, H_2O, NH_3, and HCN by high-energy β and γ particles promoted the formation of molecules such as formaldehyde, methane, carboxylic acids, and amino acids. Isotopic fractionation effects: Overlaying radioactive photolysis with photochemical processes generates mass-independent fractionation signals like O-MIF and S-MIF, some of which have been observed in meteorite samples. These findings indicate that the protoplanetary disc served not only as a physical site for planetary formation but also as a radiation-driven chemical laboratory.

Geochemical Evidence for Radiation–Metabolism Coupling

The detection of multiple amino acids, nucleoside precursors, and organic acids in the Mochisen meteorite suggests that the radioactive environment may have directly contributed to the formation of early metabolic substrates [34]. Integrating the radiation–metabolism coupling theory, the following chain can be proposed:

Radiation decay energy→ → Formation of small molecules (CO, H_2, HCN) → Synthesis of organic molecules (amino acids, nucleosides) → Accumulation of metabolic precursors. This process exhibits functional continuity with subsequent microbial metabolism. For instance: ^{26}Al, ^{60}Fe, ^{238}U, ^{232}Th, ^{40}K, ^{87}Rb, ^{147}Sm, etc., where radiation-provided electrons resemble electron flows in modern respiratory/photosynthetic chains; Radiation-driven organic synthesis exhibits chemical docking with primordial metabolic networks (e.g., the acetyl-CoA pathway, Strecker synthesis). Consequently, the radioactive signatures within meteorites such as the Mochisen meteorite may be regarded as natural experimental records of radiation–metabolism coupling.

The Site of Radiation–Metabolism Coevolution: The Planetary Disc

This evidence suggests that the origin of radiometabolic co-evolution occurred not on Earth, but within the solar protoplanetary disc and planetary disc phases. Within the planetary disc, Radioisotopes and ultraviolet/X-ray irradiation jointly drove complex organic synthesis, generating metabolic precursors. Within planetesimals and meteorites: These precursors were stored and underwent further evolution through radiothermal heating and water-rock reactions. In the early Earth, through meteorite bombardment, Earth inherited this 'radiation-metabolism legacy', upon which biological metabolism developed. This perspective supports the universality of the radiation-metabolism co-evolution theory: the evolution of life and planetary atmospheres is a product of the protoplanetary disc-planetesimal-Earth continuum, rather than an isolated Earth-specific anomaly.

The high abundance of long-lived and short-lived radioactive isotopes (SLRs, LLRs) in the Murchison meteorite, alongside the coexistence of their decay products with organic matter, indicates: A more intense radioactive environment existed in the early solar system than in Earth's modern crust; Radiation energy not only shaped the physical structures of planetesimals and meteorites but also participated in prebiotic chemical processes; The radiometabolic coupling and co-evolution occurred within the protoplanetary disc, with Earth's life merely inheriting this cosmochemical and evolutionary chain.

Significance of Long-Lived Radionuclides in the Mochison Meteorite: Nebular Legacy and Long-Term Radiation Background

The Mochison meteorite preserves decay records of short-lived radioactive isotopes (SLRs, e.g., ^{26}Al, ^{60}Fe) while also containing long-lived radioactive isotopes (LLRs, e.g., ^{238}U, ^{232}Th, ^{40}K) similar to those found on Earth. Though their abundances do not exhibit anomalous enrichment, subtle anomalies in their isotopic ratios relative to decay products (e.g., Pb, Sr, Nd systems) provide crucial clues about early solar system nucleosynthesis and material differentiation [454]. These findings indicate that Earth shares a common origin with carbonaceous chondrites, both inheriting the radioactive legacy of the same protoplanetary disc.

Within the framework of radiometabolic coupling and co-evolution, LLRs hold particular significance: they release low-intensity energy over billions of years, sustaining liquid water–hydrothermal systems within planetesimals and early planets [259]. The persistent radiation environment provides a stable chemical driving force for molecular cleavage and radical generation [455]. On the timescale of life's evolution, LLRs constitute a long-term background energy source, complementing the short-term chemical triggers provided by short-lived nuclides.

Thus, the long-lived nuclides in the Mochison meteorite serve not only as a planetary dating benchmark but also as enduring evidence for the chemical backdrop of life. They suggest that the stage for radiometabolic co-evolution was set within the protoplanetary disc, with the emergence of terrestrial life merely continuing this cosmic chemical narrative.

The significance of long-lived radioactive isotopes (LLRs) and their varying concentrations in the Earth's crust

Significance of Long-Lived Radionuclides in the Mochison Meteorite—Nebular Legacy and Long-Term Radiation Background

The Mochison meteorite not only preserves decay records of short-lived radionuclides (SLRs, such as ^{26}Al and ^{60}Fe), but also contains long-lived radionuclides (LLRs, such as ^{238}U, ^{232}Th, and ^{40}K) similar to those found on Earth [449]. Though their abundances do not exhibit anomalous enrichment, subtle anomalies in isotope ratios and decay products (e.g., Pb, Sr, Nd systems) provide crucial clues about early solar system nucleosynthesis and material differentiation [259]. These findings indicate that Earth and carbonaceous chondrites share a common origin, both inheriting the radioactive legacy of the same protoplanetary disc. Within the framework of radiometabolic coupling and co-evolution, LLRs assume particular significance: their low-intensity energy release over billions of years sustains liquid water–hydrothermal systems within planetesimals and early planets; the persistent radiation environment provides a stable chemical driving force for molecular cleavage and radical generation; On the timescale of life's evolution, LLRs constitute a long-term background energy source, complementing the short-lived chemical triggers provided by short-lived nuclides [140]. Thus, the long-lived nuclides in the Mochison meteorite serve not only as a benchmark for planetary dating but also as enduring evidence supporting the chemical backdrop of life. They suggest that the stage for radio-metabolic co-evolution was set within the planetary disc itself, with the emergence of life on Earth merely continuing this cosmic chemical narrative.

Distinction between Long-Lived Radionuclide (LLR) Abundances in the MOCHISON Meteorite and Earth's Crust/Mantle

Mochisen Meteorite Versus Average Earth Crust Levels

The Mochisen meteorite (carbonaceous chondrite, CM2) represents primordial solar system material, exhibiting abundances of long-lived isotopes (^{238}U, ^{232}Th, ^{40}K, etc.) that are typically higher than the average values found in modern Earth crust. Reason: Earth's differentiation — during planetary formation, stony-rich elements like uranium (U), thorium (Th), and potassium (K) underwent partitioning: some migrated into the mantle; others entered the crust (particularly concentrated in granitic regions); their concentrations are relatively low in oceanic crust and mantle. The "dilution effect" in Earth's surface layers — the Earth's crust is generally rich in silicon and poor in radioactive elements, whereas meteorites have not undergone extensive differentiation and thus remain relatively "enriched" in these elements.

Preservation of primordial solar nebula composition — the Mochison meteorite is essentially an unprocessed "raw material package", exhibiting higher LLRs content than the crustal average.

Why cannot a direct comparison be made with the mantle?

The abundance of radioactive elements in the mantle and meteorites is actually quite similar: this is because the Earth as a whole (Mantle + Core + Crust) shares a highly similar chemical composition with carbonaceous chondrites (both representing the average composition of the solar nebula). However, the crust has undergone differentiation and recycling, resulting in lower average values. Thus, if you compare Mochison vs. the mantle, the difference is negligible; but if you compare Mochison vs. the crust, you observe that meteorites are more "enriched" in radionuclides.

What does this indicate? The outcome of planetary differentiation

During Earth's formation, radionuclides were redistributed across different layers (mantle, crust, core), resulting in lower average concentrations at the surface. Meteorites, however, retain 'undifferentiated primordial material', hence their relatively higher concentrations. Meteorites serve as archives of planetary radioactive heritage; Mochison's high LLRs content indicates it preserves the primordial radioactive background of the protoplanetary disc. Compared to Earth's surface, it more closely approximates the 'pre-biotic energy environment'. Significance of radiometabolism co-evolution: This demonstrates that subsequent crustal conditions do not determine life's radiometric background, but rather are inherited from protoplanetary disc material. In other words, the energy source for radiometabolism co-evolution is a "cosmic legacy," not unique to Earth.

The LLRs content in the Mochison meteorite is indeed higher than Earth's "crustal average". When compared to the mantle, they are closer, as the mantle represents Earth's overall chemical composition. It indicates that meteorites are direct samples of the solar nebula's radioactive environment. In contrast, Earth's crust is merely a differentiated "secondary chemical environment." Consequently, the radiometabolic background inherited by life is thus closer to meteorites than to modern crustal materials.

Significance of Mochison meteorite LLR abundances relative to Earth's crust

Compared to Earth, the long-lived radioactive isotopes (LLRs, such as ^{238}U, ^{232}Th, ^{40}K, ^{87}Rb, etc.) preserved in Murchison meteorites exhibit abundances markedly distinct from the crustal average [455]. Overall, the abundances of these elements in meteorite samples are typically higher than the modern crustal average, yet closer to the chemical composition of the mantle and the Earth as a whole [259]. This discrepancy stems from planetary differentiation: during Earth's formation, stony elements like uranium, thorium, and potassium redistributed between the mantle, crust, and core. Subsequent long-term magmatic differentiation and plate cycling diluted their average abundance in the crust. In contrast, Mochisen meteorites, as primordial stony remnants untouched by extensive melting, preserve the original composition of the solar nebula [455].

This contrast reveals two significant implications:

Earth-Meteorite Homogeneity

The LLR abundances recorded in Mochison meteorites more closely match the overall composition of Earth (particularly its mantle), indicating that terrestrial material and carbonaceous chondrites share a common radioactive heritage reservoir.

Inheritance of the Radiation–Metabolic Environment

The LLR content within Earth's crust is insufficient to represent the actual radiation environment experienced by early life. Life's origin inherited the primordial radiological backdrop of the protoplanetary disc–meteorite phase, not the 'secondary environment' of the modern crust. In other words, life's radiological–metabolic framework aligns more closely with the 'nebular archives' preserved in the Mochison meteorite than with Earth's post-differentiation chemical patterns.

Consequently, the comparison between Mochisen meteorite LLR abundances and terrestrial crust reinforces the conclusion that the origin of radiometabolic co-evolution lies in the protoplanetary disc and planetesimal stages, with Earth merely perpetuating this legacy.

Summary and Outlook: Analysis of Long-Lived Radioactive Isotopes (LLRs) in the Murchison Meteorite Yields the Following Insights

Firstly, the Mochison meteorite preserves not only decay evidence for short-lived radioactive isotopes (SLRs, such as ^{26}Al and ^{60}Fe), but also contains substantial LLRs (^{238}U, ^{232}Th, ^{40}K, ^{87}Rb, ^{147}Sm, etc.). Although the absolute abundances of these isotopes are similar to those in the mantle and do not exhibit abnormal enrichment, they are higher than the modern crustal average. It is because the crust has undergone dilution during planetary differentiation and long-term geological cycling, whereas meteorites retain the primordial radioactive composition of the solar nebula. Thus, the Mochison meteorite serves, in a sense, as a "time capsule" of the planetary radiation background.

Secondly, the sustained decay of LLRs provided long-term energy maintenance for planetesimals and planets. Unlike the intense heating of SLRs over millions of years, LLRs slowly released energy over billions of years, ensuring the existence of liquid water and hydrothermal systems within planetesimals and early planets. This energy background was crucial for sustaining radiochemistry, molecular synthesis, and the evolution of potential metabolic networks. Thus, the radiation–metabolism coupling is not an instantaneous "trigger event" but a protracted process spanning billions of years.

Finally, comparisons between meteorites and terrestrial crustal LLRs reveal a significant fact: the radiative environment inherited by life more closely resembles that of meteorites than modern crust. In other words, the energy and chemical framework of terrestrial life constitutes a legacy from the protoplanetary and planetary stage, rather than an accidental product of later crustal differentiation. This discovery reinforces the core proposition of the radiometabolism co-evolution theory: the emergence of life is intrinsically linked to the radioactive environment of the protoplanetary and planetary disc, with Earth merely being a recipient of this universal process.

Outlook: Future Research Should Focus On

Isotopic comparisons between meteorites and the mantle — Refining Pb–Pb, Rb–Sr, and Sm–Nd dating further to clarify radiogenic background differences between Earth and meteorites. Radiochemical simulation experiments — Reconstructing water–rock–organic systems under LLRs radiation fields in laboratories to validate their role in molecular synthesis and metabolic network formation. Planetary disc universality — Integrating exoplanetary disc observations to test whether the radiation–metabolism framework represents a cosmic commonality rather than an Earth-specific anomaly.

Distinct Significance of Short-Lived Radioactive Isotopes (SLRs) and Long-Lived Radioactive Isotopes (LLRs):

In addition to short-lived radioactive isotopes (SLRs, such as ^{26}Al, ^{60}Fe, ^{53}Mn, ^{129}I), the Mochison meteorite and terrestrial materials also contain significant quantities of long-lived radioactive isotopes (LLRs). These isotopes, with half-lives in the range of 10^8–10^{10} years, persist to the present day and constitute a significant source for long-term planetary internal heating and radiochemical processes [140].

The radiogenic legacy in meteorites: The coexistence of these LLRs with products of short-lived nuclides in the Murchison meteorite indicates their fixation into solids during nebular condensation and the early protoplanetary disc phase. They not only supplied energy for meteorite heating and organic chemistry but also provided a persistent background for long-term radiometabolic environments [452].

Radiation–Metabolism Co-Evolution Perspective

Short-lived nuclides (^{26}Al, ^{60}Fe) dominated intense early energy pulses within the protoplanetary disc and planetary disc, driving stony-hydrothermal reactions and primordial organic synthesis [452]. Long-lived nuclides (^{238}U, ^{232}Th, ^{40}K, etc.) provided sustained stable energy, maintaining planetary interior activity and surface radiation backgrounds to support life's continuous evolution.

Integration of SLRs and LLRs: This constitutes a complete radiometabolic co-evolutionary energy chain: SLRs→initial chemical triggering; LLRs→long-term environmental maintenance. SLRs (^{26}Al, ^{60}Fe, etc.): short-lived but with intense energy release, acting as triggers for protoplanetary disc and planetesimal internal chemistry. LLRs (^{238}U, ^{232}Th, ^{40}K, etc.): long-lived with slow energy release, forming the sustaining backdrop for planetary long-term evolution and life persistence. The two isotope types form a complementary temporal framework: SLRs → Trigger (energy bursts on a million-year timescale); LLRs → Sustain (energy continuity on a billion-year timescale). It aligns precisely with the multi-stage framework of the Radiation–Metabolism Coupling and Coevolution Theory: originating in the protoplanetary disc (SLR-driven), and persisting through planetary evolution (LLR-sustained) [456].

Energy Release and Planetesimal Internal Maintenance

During the early formation of the Solar System, long-lived radionuclides (^{238}U, ^{232}Th, ^{235}U, ^{40}K, ^{87}Rb, ^{147}Sm, etc.) had already been injected into the protoplanetary nebula by preceding supernovae and stellar evolution. Compared to short-lived radionuclides (^{26}Al, ^{60}Fe), these long-lived radionuclides (LLRs) are distributed uniformly across the entire solar system. Planetesimals incorporated these LLRs during their formation, establishing them as long-term sources of internal energy and radiation. Energy release and internal planetesimal maintenance: Short-lived radionuclides (SLRs, e.g. ^{26}Al) provided intense heating during the initial millions of years, triggering planetesimal melting, differentiation, and hydrothermal convection. Long-lived radionuclides (LLRs) decay slowly but release energy continuously over timescales of hundreds of millions to billions of years: maintaining a low-temperature heat source within the planetesimal, preventing complete cooling. Supports prolonged water–rock interactions, sustaining liquid water environments (even within small bodies). Maintains a radiation background, delivering a low-dose ionizing energy flux. It implies that even after short-lived radionuclides have decayed away, a potentially habitable environment persists within the asteroid.

Crucial Significance for Biochemical Metabolic Sustainment

Maintaining liquid water, heat released from LLR decay (particularly ^{238}U, ^{232}Th, ^{40}K) helps sustain partial melting of ice within asteroids, forming subsurface oceans or hydrothermal systems. It parallels the "subsurface oceans" observed in modern icy moons like Europa and Enceladus. Providing long-term radiation-driven chemical energy: α, β, and γ radiation can sustainably cleave molecules such as H_2O, CO_2, and NH_3, yielding H_2, O_2, hydroxyl radicals, and reducing gases. These small molecules serve as fundamental "fuels" for early metabolism. Sustained metabolic pressure and adaptation: Persistent low-dose radiation necessitates continuous evolution of radiation-resistant and antioxidant mechanisms (e.g., DNA repair, ROS scavenging) within potential microbial systems, driving metabolic network complexity. It parallels radiation-metabolism adaptation mechanisms observed in terrestrial cyanobacteria, archaea, and radiation-tolerant bacteria (e.g., Deinococcus).

Planetary Disk–Earth Evolution Continuity

During the planetary disk phase, SLRs provided "chemical triggering", while LLRs provided "long-term maintenance". In planetesimals and meteorites, LLRs sustained hydrothermal circulation for hundreds of millions of years, potentially fostering primordial metabolic systems. In the early Earth, it inherited this radiogenic background. Life's origin remained regulated by LLRs (mantle convection, atmospheric volatilization, long-term radiogenic environment). Conclusion: Long-lived radioisotopes function as "biochemical metabolic sustainers" within planetesimals: They prevent rapid cooling after short-lived nuclides decay; provide sustained thermal and radiogenic energy, maintaining liquid water and radiogenic chemical environments; and drive radiation-resistant and antioxidant adaptations within metabolic systems, forming a long-range driving force for "radiation-metabolism co-evolution". In other words: short-lived nuclides ignited the spark of life, while long-lived nuclides sustained its flame.

Analyzing SLRs and LLRs through the "Radiation-Metabolism Coupling" lens

SLRs, Short-Term Chemical Triggers

Short-lived radionuclides (SLRs, e.g., ^{26}Al, ^{60}Fe) possess half-lives of mere millions of years [140]. During the solar system's early formation (<10 Myr), they delivered immense energy pulses: heating planetesimals → to induce internal melting and differentiation; triggered water–rock reactions → hydrothermal systems; intense radiochemistry → synthesized amino acids, nucleoside precursors, and organic molecules; this equated to instantly stoking the "chemical boiler", initiating prebiotic chemical reactions.

LLRs, Long-Term Environmental Maintenance

Long-Lived radionuclides (LLRs, e.g. ^{238}U, ^{232}Th, ^{40}K) with half-lives in the billion-year range. They release low-intensity yet persistent energy within planetesimals and early planetary interiors: sustaining liquid water environments (subsurface oceans, hydrothermal systems) for hundreds of millions of years; continuously generate low-dose radiation (→) that cleaves H_2O/ CO_2 to form H_2, O_2, and free radicals; provide a stable energy background preventing abrupt environmental cooling or chemical reaction cessation; this "gentle, enduring furnace" affords chemical reaction chains sufficient time to accumulate, cycle, and optimise.

Is hundreds of millions of years sufficient to generate life? Evidence from Earth suggests that Earth formed approximately 4.5 billion years ago, with signs of life potentially emerging around 4.1 billion years ago (zircon isotope evidence). It implies a transition from a "chemical planet" to a "living planet" within less than 400 million years. Considering the continuity between protoplanetary discs, meteorites, and Earth, SLRs initiated the "organic chemical explosion" within the first million years; LLRs subsequently sustained the "metabolic environment" for hundreds of millions of years, enabling organic compounds to evolve towards self-organization and self-replication gradually. Thus, the hundreds of millions of years of LLRs' persistence may represent a plausible time window for life's emergence within protoplanetary disc planetesimals.

Conclusion

SLRs: Provided a "lightning-like trigger", synthesizing vast quantities of precursor molecules. LLRs: Provided a "prolonged incubator", sustaining liquid water and radiation backgrounds, enabling chemistry to transition towards life gradually. Theoretically and based on Earth evidence, the SLRs → LLRs energy relay chain is sufficient to achieve the leap from inorganic chemistry to life's origin over hundreds of millions of years. It strengthens the plausibility of the Radiation–Metabolism Coevolution Theory and supports the view that "coevolution began within the protoplanetary disc".

SLRs–LLRs Relay and the Temporal Window for Life Emergence

Short-Term Chemical Triggering by SLRs

Short-lived radionuclides (SLRs) such as ^{26}Al (half-life 0.7 Myr) and ^{60}Fe (half-life 2.6 Myr) produced intense heating and radiation effects during the solar system's first few million years [451]. These induced internal melting and hydrothermal circulation within planetesimals, facilitating complex chemical reactions at mineral–water interfaces [259]. Radiation energy triggered the cleavage and resynthesis of CO_2, H_2O, NH_3, and HCN, yielding organic molecules such as amino acids, carboxylic acids, and nucleoside precursors [34]. Thus, SLRs function as chemical "igniters", providing rapid and high-energy triggering for prebiotic chemical reactions.

Long-Term Environmental Maintenance by LLRs

Long-lived radionuclides (LLRs) such as ^{238}U (4.47 Gyr), ^{232}Th (14 Gyr), and ^{40}K (1.25 Gyr) continuously release heat and radiation over billions of years [455]. They maintained low-intensity heating within protoplanetary bodies and early planets, preventing abrupt environmental cooling. It provided conditions for the long-term existence of liquid water and hydrothermal systems. Low-dose radiation continuously generates H_2, O_2, and free radicals, keeping chemical systems active. This gentle, persistent energy background offered a "nurturing environment" for organic chemistry to gradually progress towards self-organization and self-replication.

The Temporal Window and Emergence of Life

Earth formed approximately 4.5 billion years ago, while the earliest signs of life may have appeared 4.1 billion years ago, as recorded in zircon isotopes [456]. It implies that within less than 400 million years, Earth completed its transition from a "chemical planet" to a "planet of life". Integrating the SLRs–LLRs causal chain: SLRs ignited organic chemical synthesis within the initial 10 million years. LLRs subsequently maintained a stable environment for hundreds of millions of years, providing the necessary timeframe for life's gradual emergence. This timescale aligns closely with the origin of life dates in the geological record, indicating that the SLRs–LLRs relay constituted the critical window for life's emergence.

Coevolutionary Perspective

This reveals that radiation–metabolism coevolution comprises two phases: SLRs phase (trigger): Delivers high-intensity energy pulses to accumulate precursor molecules rapidly. LLRs phase (sustaining): providing sustained background energy enabling the evolution of chemical–metabolic networks. It indicates that the origin of radiation–metabolism co-evolution was not confined to Earth, but commenced during the protoplanetary disc and planetesimal stages, with Earth merely inheriting this evolutionary chain.

The Main Thread of Radiation–Metabolism Coevolution

Through comparative analysis of short-lived radioactive isotopes (SLRs) and long-lived radioactive isotopes (LLRs), alongside discussion of cyanobacterial and meteorite evidence, a continuous pathway is proposed from the cosmic radioactive background to the emergence of life.

Radioactivity

The Cosmic Energy Legacy. The solar protoplanetary disc enriched numerous radioactive isotopes, including SLRs (e.g., ^{26}Al, ^{60}Fe) and LLRs (e.g., ^{238}U, ^{232}Th, ^{40}K). SLRs provided intense heating and radiation over millions of years, triggering stellar-internal melting and radiochemical reactions; LLRs continuously released low-intensity energy over billions of years, sustaining long-term activity within the water– rock–organic matter system. Isotopic anomalies preserved in the Mochison meteorite demonstrate that this radiation background constitutes a universal legacy of the protoplanetary disc.

Chemistry

Radiation-driven prebiotic synthesis. Within planetesimals and meteorites, radiative energy continuously cleaves molecules such as H_2O, CO_2, NH_3, and HCN, generating free radicals and reducing gases. These products undergo further reactions on mineral surfaces and within hydrothermal systems, synthesizing organic molecules including amino acids, nucleoside precursors, and peptides. SLRs provided "lightning-like triggers", while LLRs offered "gentle, prolonged furnaces"; together they sustained the continuity of prebiotic chemistry [34].

Metabolism

Radiation–Metabolic Coupling and Microbial Adaptation The electron flux and radiation environment provided by radiation exhibit functional analogies with early metabolic processes: free radicals and electron flux → correspond to electron transport in primitive respiratory/photosynthetic chains; sustained radiation pressure → drives the emergence of antioxidant and radiation-resistant metabolic mechanisms [457]. Cyanobacteria represent a pivotal lineage: integrating light energy utilization, radiation resistance mechanisms, and oxygen-producing metabolism, they embody the biological continuation of radiation–metabolism co-evolution [458].

Atmosphere

From CO_2–N_2 to O_2–N_2, cyanobacterial oxygenic photosynthesis triggered the Great Oxygenation Event (GOE, ~2.4 billion years ago), transforming the atmosphere from CO_2–N_2 dominance to O_2–N_2 dominance [459]. Sulphur isotope anomalies (the disappearance of S-MIF) provide direct evidence for atmospheric oxygenation [460]. It indicates that radiometabolism co-evolution not only operates at the molecular and metabolic levels, but also shapes the atmospheric environment on a planetary scale [461]. Following the transformation of Earth's atmosphere, higher forms of life, such as eukaryotic organisms, subsequently emerged.

Life

The outcome of radiometabolic co-evolution. From planetary discs to Earth, radioactive isotopes provided the energy framework that triggered + and sustained: SLRs → rapid initiation of prebiotic chemistry; LLRs → long-term maintenance of metabolism and environment [289]. Within this framework, chemical reactions progressively evolved towards self-organization and self-replication, ultimately giving rise to life [34]. Thus, life is not an Earth-specific anomaly, but rather the inevitable continuation of the planetary disc's radioactive background.

Radiation → Chemistry → Metabolism → Life (bacteria)→ Atmospheric transformation → Life Evolution (eukaryotes) form a Continuous Evolutionary Thread

The origin of radiation-metabolism co-evolution lies within protoplanetary and planetary discs, persisting through planetesimals and meteorites, culminating in Earth's large-scale reshaping of life and atmosphere. This model not only explains life's emergence but also reveals the central role of radioactive isotopes as the "cosmic energy legacy" [403].

The Central Dogma of Cellular Protein Translation in Protoplanetary and Planetary Disks: "Optimization and Coordination"

Life's evolution lacks any 'pre-planned' consciousness, yet through prolonged natural selection and systemic coupling, it manifests effects akin to 'optimization algorithms (iterative refinement)' and 'coordinated planning (multi-constraint synergy)'. The genetic code (64 codons → 20 amino acids + start and stop signals) exemplifies this [462]. Within the protoplanetary disc and its planetesimals, life not only constructed all enzymes we observe today—including DNA polymerase for DNA replication and transcriptase for DNA-to-RNA transcription—but crucially, the central dogma of cellular protein translation was also established within the solar system's protoplanetary or planetary discs.

Why Nearly all Life Employs the "Triplet Code"

The trade-off between information capacity and computational cost itself resembles an 'optimization': at least 20 amino acids plus one stop signal require ≥ symbols, totalling ≥ 21 symbols. A single base has four possible forms (A, C, G, U). A diplet can represent $4^2=16$ (less than 21, insufficient); a triplet can represent $4^3=64$ (greater than or equal to 21, sufficient) [641]. Thus, the "triplet" is the shortest code length meeting requirements: it satisfies information capacity while avoiding the costs of tetrads—slower translation, longer genes, and higher error rates [464]. It is a classic "cost minimization" optimization outcome [465].

Why 64→ 20 (Redundancy) is Better

section demonstrates "systemic coordination" (not conscious planning, but cross-component synergistic constraints): Error tolerance and robustness: Synonymous codons mean single-base mutations or translation errors often still yield amino acids with identical/similar physicochemical properties, reducing functional catastrophe risks (error minimization) [466]. Wobble pairing and tRNA economy: The third position often permits "wobble" pairing, reducing required tRNA types and total quantity—conserving resources and enhancing speed. It aligns with ribosomes, tRNA modifications, and aminoacyl-tRNA synthetases (aaRS), constituting system-level coordination [467]. Reliability of Start/Stop Signals: AUG serves as both a start codon and a methionine codon, without expanding the alphabet; UAA/UAG/UGA function as stop signals, providing reliable termination and cooperating with release factors [468-470]. Expression Efficiency and Preference: Preferences for "optimal codons" across different organisms/tissues (related to tRNA abundance, GC content, metabolic cost) further demonstrate localized "optimization" [471].

The Shadow of "Optimality": Local Stepwise Optimization and Robustness

Minimizing error costs: The standard genetic code incurs significantly less "damage" from point mutations/misinterpretations than random codes (numerous studies comparing tens of thousands to millions of random codes place the standard code's robustness in the top quantiles) [472]. Speed-accuracy-resource trade-offs:

Compromises between codon length, synonymous redundancy, tRNA quantity, and amino acid synthesis costs resemble a long-term “multi-objective optimization” [473]. Codon Usage Bias: Highly expressed genes tend to utilize codons matching high-abundance tRNAs, further enhancing translation efficiency [474].

Echoes of the “Coordination Approach”: Cross-Modular Synergy and Path Dependence Co-Evolutionary Networks

Codon allocation, the two major classes of aaRS, tRNA modifying enzymes, ribosomal structure, and amino acid biosynthetic pathways co-evolve. Altering any component triggers systemic changes, imposing constraints for “effective coordination”. Gradual Expansion and “Freezing Events”: Initially encoding only a few amino acids, the system progressively expanded and converged under horizontal gene transfer pressures, ultimately “locking” into near-universal codons—demonstrating the compatibility “coordination” of large systems [475].

Variants and Plasticity (Re-optimization Within Constraints)

Mitochondria and certain protists exhibit codon variants (e.g., UGA encoding Trp, UAG encoding Gln); similarly, the UGA/SECIS system introduces selenocysteine, while the UAG/PYLIS system introduces pyrrolysine—demonstrating that local reoptimisation and functional expansion remain possible within overall constraints [476-478].

In summary, the “triplet” and “64→20 redundancy” embody capacity-cost-robustness optimization; the co-evolution of codon-tRNA-aaRS-ribosome-metabolic pathway reflects cross-level coordination (synergistic constraints) [479]. Neither represents conscious design, but rather the emergent outcome of long-term natural selection within complex networks. A pivotal argument in this paper is metabolic primacy—that metabolism ultimately dictates the establishment of genetic information [480]. Whether codons selected diplets, quadruplets, or ultimately triplets, the goal was to translate RNA into protein with maximum energy economy and precision, with the critical saving being in tRNA numbers [481]. The abundance of amino acids discovered in the Mochisen meteorite and other meteorites indicates a substantial surplus. Carbon structures associated with fullerenes may have played a decisive role in the emergence of the triplet codon system [482].

From Protoplanetary Discs, Planetary Discs and Planetesimals, to Migratory Birds Traversing Hemispheres

What connection might exist between the birds we now observe soaring through the skies on their migratory journeys between hemispheres and the bacteria inhabiting ancient protoplanetary or planetary discs? What possible connection might they have with this paper’s central argument—the hypotheses of “radiation-metabolism coupling” and “radiation-metabolism co-evolution” in the origin of life? This question appears rather complex, involving animal behaviour, neuroscience, evolutionary biology, and biophysics. The answer synthesizes several aspects below, rather than being an either/or choice.

Navigational Mechanism: Predominantly ‘Magnetoprotein’, Supplemented by ‘Starlight’

Bird navigation constitutes a complex, multisensory integrated system. Regarding the core aspect of “migrating along magnetic field lines” in this question, the primary reliance is on the brain’s magnetic sensing mechanism, not starlight.

Role of Starlight

Starlight (particularly the rotation of constellations) assists birds in determining macro-directions (e.g., in the Northern Hemisphere, Polaris indicates north). It serves as a visual cue for orientation, especially crucial for nocturnal migrants. However, it cannot provide the precise, vectorized “navigational map” information (including position, direction, and inclination) offered by the magnetic field.

The Core Role of Magnetoreceptive Proteins

The prevailing scientific view holds that birds perceive the geomagnetic field through a light-driven quantum biological mechanism, centred on a specialized magnetoreceptive protein. This process is far more complex than a simple “compass”.

Key Protein

This protein, Cryptochrome 4 (Cry4), is located in the avian retina [483].

Mechanism of Action: Light Activation: Light (particularly blue light) strikes the Cry4 protein in the retina. Quantum Effect: Light activation triggers electron transfer within the protein, generating a pair of “radical pairs”. These two electrons exist in a peculiar state of quantum entanglement. Magnetic Field Modulation: The strength and direction of the Earth’s magnetic field exert an extremely subtle influence on the quantum spin states of these two electrons, thereby altering the lifetime and chemical properties of the radical pair. Signal Conversion: This altered quantum state is ultimately converted into a chemically recognizable signal for cells. Visual Superposition: The brain (likely within visual processing areas) superimposes this magnetic signal onto visual imagery. Thus, birds may “see” or “perceive” the magnetic field as if overlaying a compass or contour map onto their normal visual world [484]. It enables them to precisely perceive the magnetic field’s intensity and inclination (horizontal near the equator, becoming vertical towards the poles), thereby determining their latitude. Thus, birds primarily rely on a specialized magnetoreceptive protein (Cry4) within the brain (retina), with starlight and other visual cues serving auxiliary and calibration functions [254].

The Ancient Origin of the Gene Encoding This Protein

The cryptochrome protein gene is exceptionally ancient within the tree of life and possesses a profound evolutionary history.

Origin

Cryptochrome evolved from another ancient class of light-sensitive proteins—photolyases. Photolyases function by utilizing blue light to repair DNA damaged by ultraviolet radiation, a fundamental process critical across all realms of life.

Widespread Distribution

Owing to their ancient origins, Cry proteins are widely distributed across plants, animals, and microorganisms. In plants, Cry proteins serve as core blue light receptors, regulating photomorphogenesis and circadian rhythms. In animals (such as Drosophila, mice, and humans), Cry proteins constitute essential components of the core circadian clock machinery, responsible for regulating diurnal rhythms.

Functional Specialization

Avian Cry4 represents a distinct member within the cryptochrome family, exhibiting specialized key amino acid sites within its protein structure. It confers significantly heightened sensitivity to magnetic fields via its free radical pairs compared to Cry4 proteins in other species (such as chickens and pigeons), and markedly surpasses that of human Cry proteins. It indicates that although the gene itself is ancient, its magnetic sensing function was reinforced and specialized through natural selection in birds (or their ancestors).

Connections with Archaea and Corresponding Genes

This gene exhibits profound homology with archaea, though the corresponding genes in archaea primarily perform other functions rather than magnetic sensing.

Direct Connections

Archaea, Bacteria, and Eukaryotes (including ourselves) all possess genes belonging to the photolyase/cryptochrome superfamily. It indicates that the common ancestor of this gene existed in the Last Universal Common Ancestor (LUCA) of all extant life or shortly thereafter [485].

Functional Divergence

In archaea and many bacteria, the primary function of these proteins remains DNA repair (i.e., acting as photolyases) or serving as blue light sensors to regulate other physiological processes. In archaea and many bacteria within protoplanetary discs or disc planetesimals, cellular DNA damage caused by H_2O_2 and other oxygen-free radicals generated by radioactive isotopes within the planetesimal necessitates DNA repair functions and other antioxidant mechanisms. Consequently, possession of genes from the photolyase/cryptochrome superfamily constitutes one of the survival "skills" acquired by these archaea and bacteria during their evolutionary journey within protoplanetary discs or disc planetesimals. Presently, no evidence exists suggesting archaea utilize such proteins for genuine "navigation" or "magnetoreception". They lack the necessity for such complex multicellular behaviours.

An Alternative Ancient Magnetosensory Mechanism

Interestingly, numerous magnetotactic bacteria (Magnetotactic Bacteria, belonging to the domain Eubacteria) do possess mineral-based magnetosensory capabilities. They synthesize chains of nanoscale magnetic particles known as magnetosomes (typically Fe_3O_4), which function like a string of compasses guiding the bacteria along geomagnetic field lines. It represents a more ancient magnetic sensing mechanism entirely independent of Cry proteins. Hypotheses suggest that certain animals (such as bees and some fish) may possess dual systems: both Cry-based magnetic sensing and magnetite (Fe_3O_4) particle-based sensing. However, the predominant mechanism in birds is believed to be Cry4-based [486].

Summary

Navigation Mechanism: Migratory birds navigate along magnetic field lines primarily through the Cry4 protein in their retinas, perceiving the magnetic field via light-driven quantum effects. Visual cues such as starlight provide supplementary directional information.

Ancient Gene Origin: Genes encoding Cry proteins are exceptionally ancient, originating from the DNA repair system (photolyase) shared by all life. These genes underwent multiple evolutionary adaptations for diverse photoreceptive functions, such as plant phototropism and animal circadian rhythms [487].

Connection to archaea: Archaea possess homologous genes to Cry proteins, though these genes primarily execute fundamental life functions like DNA repair rather than complex navigation. The Cry4 protein utilized by birds for magnetic sensing represents a functional innovation achieved through specific evolution within the animal kingdom, stemming from their ancient ancestral genes. In short, the blueprint for the 'magical' protein birds use for navigation already existed in archaea billions of years ago. However, within the protoplanetary disc or disc planetesimal, DNA damage in the archaea and many bacteria present there was inevitable due to the production of H_2O_2 and other oxygen-free radicals from radioactive isotopes within the planetesimal. It necessitated the development of DNA repair functions and other antioxidant mechanisms. Thus, possessing genes from the photolyase/cryptochrome superfamily became one of the survival 'skills' for these archaea and bacteria during their evolution within the protoplanetary disc or planetesimals. This protein was initially merely a 'repairman' sustaining basic life functions. Through prolonged evolution, this tool was reshaped by natural selection, ultimately transforming into a sophisticated quantum navigator in birds.

Thus, observing modern bird migration indirectly reveals how archaea and bacteria, facing DNA damage from radioactive isotope-generated oxides within protoplanetary discs or planetary disc planetesimals, were compelled to evolve antioxidant and DNA repair capabilities. It gave rise to the photolyase/cryptochrome superfamily genes we now observe in archaea and bacteria. It provides further corroboration for the "radiation-metabolism coupling" and "radiation-metabolism co-evolution" hypotheses concerning life's origins.

Why do viruses, archaea, and bacteria possess radiation resistance far exceeding that of humans and other mammals?

As previously discussed, migratory birds possess Cry4 proteins evolved from genes within the photolyase/cryptochrome superfamily. This superfamily exhibits extremely close genetic ties to archaea and bacteria. It indirectly supports the "radiation-metabolism coupling" and "radiation-metabolism co-evolution" hypotheses concerning the origins of life. Furthermore, the fact that bacteria and viruses exhibit significantly higher levels of these characteristics than humans and other mammals provides direct, tangible evidence in support of these hypotheses.

Radiation Resistance Comparison: Simple Life vs. Complex Life

Organism Type	Typical Representative	Radiation Tolerance (Gy)	Key Resistance Mechanisms
Human	Homo sapiens	~4–10	DNA repair, apoptosis
Bacteria	E. coli	~100–1000	SOS response, basic repair
Archaea	Deinococcus radiodurans	~5,000–30,000	High-efficiency recombination, Mn^{2+}-$^{+}$ Antioxidant, polyploidy
Viruses	Multiple	>10,000	Physical protection, simple structure

*Note: 1 Gy (Gray) = 1 J/kg, a unit of absorbed dose. The lethal dose for humans is approximately 4–10 Gy, whereas *D. Radiodurans *can withstand 5000 Gy.*

Core Logic of the "Radiation-Metabolism Co-Evolution" Hypothesis for Protoplanetary Discs and Disc-Dwelling Protoplanets

This hypothesis posits that the origin and early evolution of life occurred within a high-radiation environment (such as protoplanetary disks and the interiors of disk-forming bodies). Consequently, life must have adapted to radiation from its inception, with its fundamental metabolism and molecular mechanisms co-evolving alongside radiation resistance, becoming deeply integrated. The logical chain is as follows:

Environmental Drivers

The early solar system was rich in short- and long-half-life radioactive isotopes (e.g., ^{26}Al, ^{60}Fe, ^{238}U, ^{232}Th, ^{40}K). Planetesimals underwent continuous radiolysis within their interiors, generating energy and the foodstuffs (H_2 and CO) upon which bacteria depend, alongside redox substrates such as H_2O_2, •OH, $O_2^{\bullet-}$, and NO_3^- .Radiation serves both as a stressor (driving selection for antioxidant+ and rapid repair mechanisms) and as an energy source (supplying electron donors/acceptors for chemosynthetic autotrophic metabolism) [260,403]. Evidence for this energy source on Earth: In deep fracture water systems, H_2 produced by radiolysis can sustain microbial communities long-term (e.g., the "monospecific ecosystem" Candidatus Desulforudis audaxviator at 2.8 km depth in gold mines), demonstrating survival via radiolysis chemical gradients without sunlight [448]. Over time, radiation resistance became fixed alongside a metabolic network fueled by radiolysis products [404].

Metabolic Origins

The earliest life processes (such as methanogenesis and acetate production via the Wood-Ljungdahl pathway) evolved to utilize substrates generated by radiation (e.g., $H_2 + CO_2$) [399].

Selective Co-Coupling

At these sites, radiation-derived metabolism (hydrogen-dependent methane/acetate production, sulphate reduction, etc.) and radiation resistance strategies ("protect proteins first, repair DNA later") mutually reinforced each other, enabling microbes not only to survive but to thrive in radioactive niches [489]. Co-evolution of resistance: Survival in this environment necessitates the simultaneous evolution of efficient radiation energy utilization (metabolism) and radiation damage defence (resistance), embedding these as core components of the blueprint of life.

Path Dependence

Subsequent, more complex life forms (eukaryotes, multicellular organisms) evolved on Earth's surface as radiation levels diminished. They lost the intense selective pressure for these ancient, energy-intensive resistance mechanisms and even discarded them due to their high costs.

Why Are Simple Life Forms More Resistant?

An Explanation via the Planetary Disk-Planetesimal Coevolution Model

Complex life did not "evolve better"; instead, it followed distinct evolutionary pathways and strategies. Simple life retained the "ancient artifacts" originating from high-radiation environments.

Viral Strategies for Radiation and Oxidative Resistance

Minimal Physical Structure Constitutes their "Resistance" Hypothesis link

Viruses may represent early life forms or their derivatives. In radiation-rich environments, their simple protein capsids and nucleic acid cores provide inherent protection. The absence of complex metabolic machinery reduces vulnerable targets—resistance essence: Not active repair, but physical tolerance. The capsid effectively shields nucleic acids, and its minuscule genome reduces hit probability. Even if fragmented, sequences readily "reconstruct" from the host. Viruses lack self-metabolism, yet their capsid structure and reliance on host repair mechanisms yield high "D_{10}" values under certain media/cryopreservation conditions. Conversely, many enveloped RNA viruses inactivate at kGy-level doses, indicating radiation resistance is highly dependent on genome type, capsid, and matrix (protein content, volume, etc.). The connection to "radiation-metabolism co-evolution" lies in the fact that viruses capable of maintaining infectivity in long-term radioactive environments have a greater chance of being preserved and transmitted alongside their host populations [490].

Viruses employ a strategy of "population diversity": rather than relying on individual viral particles possessing exceptional resistance to radiation and oxidation, the virus as a whole ensures survival and replication through its vast genetic diversity, simple structure, and extremely high mutation/recombination rates. It guarantees that a proportion of viral variants will persist and replicate [491]. It constitutes a strategy of "probability" and "diversified investment" [492].

Virus Classification

Based on Genetic Material Properties and Replication Strategies The International Committee on Taxonomy of Viruses (ICTV) primarily classifies viruses based on their nucleic acid type and replication strategy. The following are all known major virus types:

- **Double-stranded DNA viruses (dsDNA), Characteristics:** Genetic material is double-stranded DNA. Their replication method most closely resembles cellular processes, typically utilizing the host cell's DNA polymerase [493]. Examples: *Poxviruses* (e.g., variola virus), *herpesviruses* (e.g., herpes simplex virus), *adenoviruses, megaviruses*, and th*e order Baculoviridae* (including most bacteriophages) [494,495].
- Single-stranded DNA viruses (ssDNA), Characteristics: Genetic material consists of single-stranded DNA. During replication, a double-stranded DNA intermediate is synthesized using the single-stranded DNA (ssDNA) as a template. Examples: Circoviruses, parvoviruses (e.g., canine parvovirus), filamentous bacteriophages (e.g., M13).
- DNA retroviruses (ssRNA-RT). Characteristics: Although their genetic material is DNA, replication involves an RNA intermediate and requires reverse transcriptase to synthesize DNA; examples include the Hepatovirus family (e.g., hepatitis B virus, HBV).
- Double-stranded RNA viruses (dsRNA), Characteristics: Genetic material is double-stranded RNA. Viral particles carry their own RNA-dependent RNA polymerase (RdRP), as host cells lack mechanisms to replicate RNA using RNA templates. Examples: Reoviridae (e.g., rotavirus).
- Negative-strand single-stranded RNA viruses (-ssRNA) are characterized by: genetic material being single-stranded RNA, yet its sequence is complementary to mRNA and cannot be directly translated. The viral particle carries its own RdRP, which is used first to synthesize positive-strand RNA. Examples: Paramyxoviridae (e.g., measles virus, Newcastle disease virus), Orthomyxoviridae (e.g., influenza virus), Rhabdoviridae (e.g., rabies virus).
- Positive-strand single-stranded RNA viruses (+ssRNA), characteristics: The genetic material itself functions as mRNA and can be directly translated into proteins by the

host ribosome. Its genome encodes RdRP for RNA replication. Examples: Coronaviridae (e.g., SARS-CoV-2), Parvoviridae (e.g., poliovirus), Flaviviridae (e.g., dengue virus, hepatitis C virus HCV).

- RNA retroviruses (ssRNA-RT) are characterized by: genetic material being positive-strand RNA, yet replication necessitates reverse transcriptase to transcribe the genomic RNA into DNA. This DNA integrates into the host chromosome to form proviruses, making them the only RNA viruses that genuinely integrate into the host genome. Examples: Retroviridae (e.g., human immunodeficiency virus, HIV, and human T-cell leukemia virus, HTLV).
- **Subviral Factors, Satellite Viruses:** Defective viruses requiring another helper virus to complete replication. Virusoids: Consisting solely of circular single-stranded RNA without a protein capsid, exclusively infecting plants. Prions: Composed solely of misfolded proteins, capable of inducing misfolding in normal homologous proteins, leading to neurological diseases (e.g., bovine spongiform encephalopathy).

Viral diversity (varied genomic types and replication strategies) represents multiple successful "solutions" for exploring the biological space of hosts. Thus, the viral world as a whole, with its vast gene pool and flexibility, enables rapid adaptation to extreme environments (such as radiation and oxidative stress). Its survival relies not on a single "super-organism" but on the collective intelligence of "one size fits all".

For Bacteria and Archaea: Resistance as a Metabolic "Symbiont-like Trait"

They form the core evidence for this hypothesis, with their resistance mechanisms directly linked to ancient metabolism:

- Highly efficient DNA repair systems, exemplified by Deinococcus radiodurans (the radiation-tolerant radiodurans). Coevolutionary link: Under sustained radiation, DNA damage is the norm rather than the exception. Thus, rapid and accurate repair capabilities constitute a core life function as fundamental as DNA replication and transcription [496]. Mechanism: D. radiodurans possesses an exceptionally efficient homologous recombination system capable of accurately reassembling hundreds of DNA fragments within hours. It likely represents a "standard feature" evolved by early life forms in radiation-exposed environments to maintain genomic integrity.
- Powerful antioxidant systems (all radiation-resistant microorganisms) co-evolutionary link: The primary by-products of radiation-induced water radiolysis are reactive oxygen species (ROS), such as ·OH and H_2O_2. Early life forms harnessing radiant energy (H_2, CO) must simultaneously address ROS toxicity. Thus, antioxidant defence and energy metabolism represent two sides of the same coin [497]. These antioxidant mechanisms include: Mn^{2++} antioxidant complexes: Deinococcus and related bacteria accumulate high concentrations of Mn^{2++}, forming complexes with small-molecule metabolites (such as peptides and phosphates) [317]. Radiation-tolerant Qibacteria exhibit cellular Mn^{2+} concentrations as high as 0.2–3 mmol/L and possess exceptionally high Mn: Fe ratios, enabling highly efficient quenching of ROS and protection of proteins from oxidative inactivation [498,499]. This approach is more direct and stable than the enzyme systems relied upon by mammals (such as superoxide dismutase, peroxidase, and catalase) [500]. Non-enzymatic antioxidants: Many archaea and bacteria utilize unique antioxidant metabolites. Non-enzymatic antioxidant systems include carotenoids, pyrroloquinoline quinones, and Dps proteins, among others [501].
- **Selection of Cellular Architecture, Co-Evolutionary Link:** Simple cellular structures better maintain internal reducing environments and resist oxidative stress. Mechanism: Absence of complex organelles (e.g., mitochondria, nuclei) avoids secondary ROS production sites and damage propagation points. Archaea's cell membranes comprise ether lipids, which are more stable and resistant to oxidation and radiation than the ether lipids found in eukaryotes and bacteria.
- **Selection of Metabolic States (e.g., Dormancy, Polyploidy), Co-Evolutionary Link:** Coping with radiation fluctuations. Mechanism: Deinococcus frequently maintains polyploid genomes, providing redundant templates for DNA repair. Many extremophiles enter dormancy, reducing metabolic activity and thereby mitigating indirect radiation damage (e.g., replication errors).

For Mammals, Including Humans: Evolutionary Trade-Offs

Our ancestors evolved in terrestrial environments with significantly reduced radiation. Radiation resistance ceased to be the primary determinant of survival, replaced instead by complexity, efficiency, and energy conservation.

- **High Cost:** Maintaining an ultra-efficient repair and antioxidant system akin to that of Deinococcus demands substantial energy and resource investment. In low-radiation environments, this represents a waste.
- **Strategic Shift:** Complex organisms adopted alternative survival strategies: "apoptosis" (programmed cell death): rather than expending substantial resources to repair a damaged cell, it undergoes programmed death and replacement. It is crucial for maintaining tissue health in multicellular organisms. The immune system eliminates cancerous or damaged cells through a process known as immune surveillance. Redundant systems, tissues with regenerative capacity, and stem cell reservoirs.
- **Larger Targets:** Our genomes are larger and more complex, with DNA packaged more densely within the nucleus, making the consequences of damage, such as double-strand breaks, more severe. Active metabolism also generates endogenous ROS, complicating the effects of external radiation.

A Unified Perspective on the "Radiation-Metabolic Coevolution" Hypothesis for Protoplanetary and Planetary Disks

The "radiation-metabolism coevolution" hypothesis provides a robust framework for understanding the distribution of radiation resistance:

Origin Determinism

Life's original purpose was to utilize radiation within radiation. The resistance of viruses, bacteria, and archaea is not a "superpower," but rather a vestige of their ancient ancestors' survival strategies. Their core metabolism (e.g., methanogenesis, hydrogen metabolism) and resistance mechanisms (efficient repair, Mn-based antioxidants) are deeply integrated traits co-evolved during the same period under the same selective pressures.

Evolutionary Path Dependence

Complex organisms like humans are latecomers to a "low-radiation environment". We evolved more economical strategies better suited to complexity (such as apoptosis and immunity), but at the cost of losing our primordial resilience to extreme radiation.

In short, it is not that simple; life forms are not "stronger" because they never left (or have consistently retained) the "high-intensity training camp" that shaped them. Complex life forms, however, shed their heavy "radiation-proof armour" after leaving the "training camp" in favour of other, more crucial skills (such as intelligence and agility).

Are octopuses extraterrestrial visitors?

Octopuses, with their unique anatomy and remarkable intelligence, are often likened to extraterrestrial visitors. How might these traits relate to the chemical composition of protoplanetary discs and the "radiation-metabolism coevolution" hypothesis for disc-bound starfish? The chemical property of PAHs (polycyclic aromatic hydrocarbons) forming quinones under specific conditions can be linked to the biological fact that octopuses are highly dependent on respiratory metabolism centred on quinones (such as ubiquinone/coenzyme Q). It is not merely an intriguing coincidence but points to a potential, fundamental adaptive strategy in the evolutionary history of octopuses and their cephalopod relatives.

Ancient, Efficient Metabolic "Toolkits"

Conservative and Efficient Metabolic Pathways

Quinones (particularly ubiquinone) serve as electron carriers, forming an indispensable component of the mitochondrial respiratory chain in nearly all eukaryotes (and many bacteria) on Earth. The octopus's high dependence on this pathway indicates it has inherited and optimized an ancient, proven, and highly efficient energy production system.

Energy Demand Matching

Octopuses are active predators possessing an exceptionally complex nervous system and energy-intensive muscular tissue (for colouration, jet propulsion, and object manipulation). This highly efficient "quinone-mediated oxidative phosphorylation" system maximizes ATP (the energy currency) extraction from each glucose or fat molecule, supporting their energy-demanding lifestyle. It is akin to possessing a high-performance engine.

Octopuses may exhibit enhanced buffering or tolerance to oxidative stress

This is the most thought-provoking point. Quinone molecules are a double-edged sword

- **Normal Function:** Within the respiratory chain, ubiquinone (UQ) safely transfers electrons via reversible redox reactions ($UQ \rightleftharpoons UQH_2$).
- **Potential Hazard:** If electrons leak, ubiquinone can generate reactive oxygen species (ROS), including superoxide, leading to oxidative damage. Exogenous quinones (e.g., those derived from polycyclic aromatic hydrocarbons, or PAHs) can also produce substantial ROS through redox cycling.

The octopus's dependence may indicate it has evolved a robust antioxidant defence system to manage this inherent risk. It could include:

- Ultra-high activity antioxidant enzymes (such as superoxide dismutase (SOD) and catalase).
- Efficient DNA repair mechanisms (as discussed in the context of radiation tolerance), since oxidative damage represents a primary mode of destruction common to both radiation and quinone toxicity.
- Specialized cellular mechanisms to ensure the "sealed nature" of the electron transport chain, minimizing electron leakage. In other words, octopuses possess not only a powerful "engine" but also a top-tier "cooling and protective system". It likely confers greater resilience than other organisms when confronting oxidative stress induced by exogenous quinones (such as those derived from environmental PAHs) or increased endogenous ROS.

This may reflect historical adaptations to specific chemical environments.

According to the "radiation-metabolism coupling" and "radiation-metabolism coevolution" hypotheses concerning the origin of life in protoplanetary discs, these discs contain substantial quantities of polycyclic aromatic hydrocarbons (PAHs), at levels one hundred million to one billion times greater than those found on the ancient Earth. The PAH content on the primordial Earth was essentially negligible. Ubiquinone (UQ), generated from PAHs via radiation and oxidation, serves as the safe electron carrier in the octopus respiratory chain through reversible redox reactions. The core function of UQ is its role as the "transport hub" of the respiratory chain. "Collecting electrons from NADH dehydrogenase (complex I) and succinate dehydrogenase (complex II)": this is ubiquinone's unique property. It is the sole component in the respiratory chain capable of simultaneously receiving electrons from two distinct pathways (NADH and $FADH_2$), thereby converging electron flows. Octopus mitochondria retain their α-proteobacterian ancestral trait, employing ubiquinone (CoQ/UQ) as a universal, highly efficient, membrane-bound, lipid-soluble electron carrier. Complex I (NADH dehydrogenase) and Complex II (succinate dehydrogenase) inject electrons into the CoQ pool, generating $CoQH_2$; $CoQH_2$ transfers electrons to cytochrome c via the Q cycle at complex III, whilst pumping protons; these electrons then proceed to complex IV via cytochrome c, where O_2 is reduced to H_2O, whilst further proton pumping occurs. The membrane-spanning proton electrochemical gradient established by complexes I, III, and IV drives complex V (ATP synthase) to synthesize ATP. It constitutes the biochemical foundation for the highly agile and mobile lifestyle of cephalopods (including octopuses). The pan-quinone-mediated oxidative phosphorylation represents the most efficient method for extracting energy from oxygen and food. Octopuses have optimized this system to its utmost potential, supporting their astonishing physiological and behavioural complexity.

Is the octopus's antioxidant capacity acquired or an innate inheritance?

Cephalopods (including octopuses) exhibit highly concentrated accumulation of ^{210}Popotassium-210within their digestive glands (accounting for over 90% of the body's total burden), which influences internal dose and exposure pathways. Why do cephalopod digestive glands accumulate ^{210}Po to such an extent?

- ^{210}Po (polonium-210) is a naturally occurring radioactive isotope within the ^{238}U (uranium-238) decay chain. With a half-life of 138.4 days, it emits high-energy alpha particles and constitutes a significant source of natural radiation in marine environments. Uranium-238 is also one of the key long-lived isotopes in protoplanetary discs and planetesimals within planetary discs. The extreme accumulation of 210Po in the digestive glands (or hepatopancreas) of cephalopods (octopus, squid, cuttlefish) represents a highly characteristic and pronounced feature. The fundamental reason lies in the chemical properties of 210Po and its behaviour within the food chain.
- **Chemical Similarity (key mechanism):** ^{210}Po bears chemical resemblance to sulphur (S) and selenium (Se). It leads organisms to erroneously process and transport it as an essential trace element. Protein binding: Po exhibits a strong

affinity for sulphur-containing amino acids within proteins, such as cysteine and methionine. Digestive glands, being organs that produce large quantities of digestive enzymes (proteins), thus become ideal "deposits" for Po.

- **Top-tier Enrichment:** Cephalopods prey on these crustaceans, small fish, and similar organisms. Due to their extremely high feeding rates and efficient assimilation, they further concentrate the 210Po accumulated in their prey within their own bodies, ultimately storing it in the digestive glands. Other fish: These also accumulate 210Po, but typically not to the extreme degree of concentration in a single organ seen in cephalopods. Their distribution may be more dispersed across muscle, bone, and viscera. Cephalopod digestive glands are notoriously highly enriched. Other animals: The digestive glands (midgut glands) of some bivalves (e.g., scallops, oysters) also accumulate 210Po, though their proportion of total body burden is generally less striking than in cephalopods.

What effect does ^{210}Po have on octopuses?

It is a crucial question, and the answer is somewhat counterintuitive. Characteristics of alpha particles: The alpha particles emitted by ^{210}Po possess high energy but extremely low penetrating power; a sheet of paper or the stratum corneum of skin can block them. Consequently, their primary hazard stems from internal radiation exposure – i.e., bombarding adjacent cells after ingestion. The wisdom of 'compartmentalization': Octopuses concentrate over 90% of ^{210}Po within the digestive gland, a non-essential organ. It represents an evolutionary adaptive strategy.

Octopus Antioxidant Strategy

Does the octopus possess an innate adaptation to exogenous PAHs? More accurately, the octopus may harbour a universal, robust cellular defence system enabling it to concurrently counter multiple chemical stresses, including PAHs and their quinone derivatives [502].

Strategies for surviving primordial life pressures originated within protoplanetary and planetary disks.

- **Robust antioxidant system:** As previously noted, octopuses possess highly active antioxidant enzymes (e.g., SOD, catalase, glutathione peroxidase) and antioxidant molecules capable of efficiently scavenging ROS generated during PAH metabolism [503].
- **Efficient Phase II Metabolic Enzyme System:** Following oxidation of PAHs to epoxides by cytochrome P450 enzymes (CYP450), Phase II enzymes such as glutathione S-transferases (GST) and UDP-glucuronosyltransferases (UGT) are required to conjugate these compounds with endogenous molecules. It enhances their water solubility, facilitating excretion [504]. The activity and diversity of such enzymes in octopuses may be considerable.
- **Efficient DNA damage repair mechanisms:** As discussed in radiation tolerance, this system can also repair damage caused by PAH-DNA adducts.
- **Efflux transporters:** Such as P-glycoprotein (P-gp), which may actively pump certain PAHs or their metabolites out of cells, reducing their intracellular accumulation.

Octopuses, owing to their highly metabolic lifestyle (which inherently generates substantial ROS) and unique feeding habits (potentially consuming prey containing natural toxins), have evolved a robust "detoxification and damage control" system. This system endows them with greater resilience and tolerance than many other animals when confronted with diverse environmental pollutants, including radionuclides and PAHs. Through the above discussion, we observe octopus metabolism and its resistance to isotopic radiation and oxidative stress. Traces of these metabolic, radiation-resistant, and antioxidant mechanisms can be discerned in life forms originating from protoplanetary discs and planetary disc planetesimals.

From "radiation-metabolism coupling" and "radiation-metabolism co-evolution" to radiation-metabolism-altered atmospheric environment-eukaryotic cells

The central theoretical hypotheses explored in this treatise are "radiation-metabolism coupling" and "radiation-metabolism co-evolution". The primary proposition posits that life within protoplanetary and planetary disks, through radioactive decay and radiolysis, receives energy and nutrients whilst simultaneously generating superoxide ions and molecules. Life cells thus evolved within this environment, acquiring resistance to both radiation and superoxide ions and molecules whilst obtaining sustenance. Proteins (Hemolithin) and bacteria such as cyanobacteria within protoplanetary and planetary disks may have consumed H_2O and CO_2 while simultaneously producing O_2 through various mechanisms. These cyanobacteria likely arrived on Earth via meteorites during the Late Heavy Bombardment (LHB) period. Owing to characteristics evolved within the protoplanetary and planetary disks, these cyanobacteria, over hundreds of millions of years following their arrival on Earth, transformed the planet's atmosphere. They shifted Earth's original atmosphere, dominated by CO_2 and N_2, into one primarily composed of O_2 and N_2. It is what we refer to as the Great Oxidation Event (GOE).

In prior discussions, we have thoroughly examined haemolithin and its significance in the origin of life [505]. Here, I revisit haemolithin to elaborate on its indirect connection to the GOE. While haemolithin played no direct role in the GOE, its identification in Acfer 086 and Allende meteorites indicates that it not only removes water within meteorites but also generates oxygen.

Previously, we noted that polycyclic aromatic hydrocarbons (PAHs) in protoplanetary discs exceed terrestrial concentrations by over one hundred million times. Consequently, in examining the relationship between PAHs and life's origins, proponents of Earth-centred origin theories cannot rely on PAHs as evidence for their postulates. Should life indeed have originated within protoplanetary or planetary discs, PAHs would constitute crucial supporting evidence. The oxidation products of PAHs and quinones, such as plastoquinone (PQ), form the metabolic mechanism of cyanobacteria, playing a pivotal role in the Great Oxygenation Event (GOE) [461].

Classification and Evolution of Cyanobacteria on Earth

Position within the Biological Classification System

Domain: Bacteria Kingdom: Typically classified within the Bacteria kingdom (formerly listed separately as the Cyanobacteria kingdom in older systems) Phylum: Cyanobacteria [506].

Its Profound Historical Significance

Cyanobacteria represent among the earliest organisms on Earth capable of oxygenic photosynthesis, with the earliest credible fossil evidence dating back 2.8–3.5 billion years. Their emergence fundamentally transformed the planet: The Great Oxidation Event: Cyanobacteria released oxygen through photosynthesis, gradually altering the anaerobic atmosphere of the primordial Earth. It culminated in the Great Oxidation Event approximately 2.4 billion years ago, laying the foundation for the subsequent evolution and proliferation of aerobic organisms (including all eukaryotic animals and plants) [507].

Origin of the Endosymbiotic Theory

Scientists propose that chloroplasts within eukaryotic plant cells evolved through symbiosis, originating when an ancient eukaryotic ancestor engulfed a cyanobacterium without digesting it [508]. Thus, cyanobacteria may be regarded as the "ancestor" of all plant chloroplasts [509].

Hemolithin as an Iron-Based Photochemical System

Similarities and Differences with the Photosynthetic System of Cyanobacteria

Photochemical Reaction Mechanism of Hemolithin: The core of hemolithin comprises an ordered structure of iron ions (Fe^{2++} / Fe^{3++}) and amino acids (particularly glycine) [505]. Upon photon irradiation, the following may occur:

- $Fe^{2++} + h\nu \rightarrow Fe^{3++} + e^{--}$ (photo-oxidation of iron)
- $2\,H_2O + 4\,h\nu \rightarrow 4\,H^+ + 4\,e^- + O_2$ (photolysis of water, releasing electrons and

It implies it may function as a photosensitizing catalytic centre, utilizing photons to hydrolyze water and release electrons and oxygen. It bears some resemblance to photosystems, though it lacks a complete electron transport chain (ETC) or pigment complex. Core significance: Should heme-containing protein truly catalyze the second reaction, it would constitute a primitive precursor to Photosystem II (PSII). PSII constitutes the core machinery responsible for "photolysis of water and oxygen evolution" in cyanobacterial and plant photosynthesis.

Cyanobacterial Photosynthetic Systems

(Chlorella, Cryptococcus, Spirulina, etc.) Cyanobacteria represent the true originators of "oxygenic photosynthesis". Their core mechanism is the utilization of the Mn_4CaO_5 cluster of Photosystem II (PSII) as the water-oxidizing complex (WOC) [507,510]. Light energy drives the Mn redox cycle, generating an electron flow:

$$2\,H_2O \rightarrow O_2 + 4\,H^+ + 4\,e^-$$

Electrons are further transferred to photosystem I (PSI), ultimately generating NADPH and combining with ATP to synthesize carbohydrates [511]. Cyanobacterial photosynthesis features highly integrated pigment complexes (chlorophyll a, phycocyanin), multi-tiered electron transport chains, and is vastly more complex than single-metal catalysis [508].

Hemolithin and Cyanobacteria: Connections and Comparisons

Similarities

- Hemolithin and cyanobacteria both utilize photons as an energy source.
- The key processes in both involve the photolysis of water and the release of electrons and protons. It constitutes the most fundamental connection; whether the hypothetical heme protein or the actual cyanobacteria, their core capability lies in utilizing light energy to split water, producing electrons, protons, and oxygen.
- The redox cycle of $Fe^{2+} \rightarrow Fe^{3+}$, in a certain sense, resembles the function of Mn clusters in cyanobacterial photosystem II [512].
- Both possess the potential to generate oxygen (i.e., "oxygenic photochemistry").

Differences

- **Different Metal Centres:** Haemolithin utilizes Fe (iron), while cyanobacteria employ Mn (manganese).
- **Complexity:** Hemolithin exhibits a primitive, single-molecule catalytic approach; cyanobacteria possess a complete membrane system, complexes, and energy-coupling mechanisms.
- **Evolutionary Significance:** Hemolithin may represent a "prototype photosynthetic system" in prebiotic chemistry; cyanobacteria were the first organisms in Earth's history to fix CO_2 and release O_2 on an enormous scale.
- **Energy Utilization Pathways:** Electrons released by haemolithin likely served only local dehydration reactions or small-molecule reduction, whereas cyanobacteria integrated electrons into complete photosynthetic phosphorylation and carbon fixation cycles.

Evolutionary Connections

Hemolithin may be regarded as a "molecular fossil" of light-driven metal catalysis, potentially providing early energy input and dehydration pathways in protoplanetary discs or meteorite environments. Cyanobacteria represent the evolutionary continuation of this "metallophotochemical→biological integration", substituting metal centres with more efficient Mn clusters and integrating them into membrane and protein complexes. It may be inferred that cyanobacterial photosynthetic mechanisms constitute an "inheritance and complexification" of primordial iron/nickel/manganese metal-catalyzed systems.

In summary, the Fe^{2+}-$^{+}$ /Fe^{3+}-$^{+}$ -driven photo-oxidation of + and its subsequent hydrolysis reaction in haemolithin share mechanistic similarities with cyanobacterial photosynthesis: both rely on metal centres, photon-driven processes, electron release, and oxygen production. However, haemolithin represents a more primitive, molecular-scale photochemical catalytic system, whereas cyanobacteria constitute its highly evolved biological continuation. Through manganese clusters and complete photosystems, cyanobacteria have fixed this reaction and transformed it into a sustainable source of atmospheric oxygen. Thus, the connection between haemolithin's reaction and cyanobacteria is one between a 'prototype principle' and a 'mature technology'. Studying the former aids our comprehension of how the latter evolved from simple origins, while also prompting reflection on the potential cosmic prevalence of life's fundamental chemical reactions.

The Relationship Between Cyanobacteria, Quinones, the Respiratory Chain, and the Photosynthetic Chain

Quinones reveal the molecular-level unity and sophistication of the living world. Quinones serve as the pivotal link between cyanobacterial respiration and photosynthesis [513]. As oxidation products of polycyclic aromatic hydrocarbons (PAHs), substances like plastoquinone (PQ) underpin cyanobacterial metabolic mechanisms and play a crucial role in the Great Oxygenation Event (GOE) [514].

Quinones constitute a class of small, lipid-soluble electron carrier molecules. Their fundamental capability lies in shuttling electrons and protons (hydrogen ions, H^+) across membranes. Upon accepting electrons and protons, they convert from the 'quinone' form to the 'quinol' form. When releasing electrons and protons, they revert from 'quinol' back to 'quinone'. This process accomplishes two tasks simultaneously: electron transfer and proton gradient establishment. The key role in cyanobacteria, and their unique feature, lies in possessing both photosynthetic and respiratory systems, both integrated within the same cell membrane (and thylakoid membrane). The quinone pool (menaquinone, plastoquinone) is precisely their shared core component.

Within the Photosynthetic Chain

- Photosystem II (PSII) photodrives water splitting, releasing oxygen while extracting electrons [515].
- These electrons are first transferred to plastoquinone (PQ) [516].
- PQ accepts the electrons and, whilst drawing in two H^+ from the stroma, transforms into PQH_2 (plastoquinone hydrate).
- $^+$P QH_2 shuttles across the membrane to the cytochrome b_6f complex, transferring electrons while releasing two H^+ ions into the periplasmic space.
- This process constitutes a crucial step in establishing the proton gradient during photosynthesis (utilized to drive ATP synthesis).

Within the Respiratory Chain

- During the breakdown (oxidation) of organic compounds (such as glucose), electrons enter the respiratory chain via carriers like NADH.
- These electrons are similarly transferred to quinone molecules (typically menaquinone or plastoquinone within the respiratory chain).
- The same process occurs: quinone accepts electrons and H^+ , transforming into hydroquinone. Hydroquinone shuttles to complex III, where it transfers electrons and pumps out H^+ .
- This process constitutes a crucial step in establishing the proton gradient during respiration, which drives ATP synthesis.

Relationship and Integration of the Photosynthetic Chain and Respiratory Chain

Within both the respiratory and photosynthetic chains, quinone molecules (such as ubiquinone, plastoquinone, and menaquinone) serve as pivotal electron- and proton-carriers: they possess a hydrophobic tail embedded within the membrane lipid bilayer. The quinone/quinol structure at the molecular head undergoes reversible two-electron/two-proton redox reactions. Thus, quinones diffuse laterally across membranes, simultaneously transferring electrons and protons from one protein complex to another. In cyanobacteria, the photosynthetic and respiratory chains share a common quinone pool (particularly the plastopirone pool, PQ). It signifies that the quinone pool serves as the common convergence point for both the photosynthetic and respiratory electron transport chains. In cyanobacteria: Photosystem II (PSII) → Plastoquinone (PQ) → Cytochrome b_6f complex → Photosystem I (PSI).

Flexible Regulation

This shared structure confers substantial metabolic flexibility upon cyanobacteria. During daylight with ample illumination, the surplus of reducing power (NADPH) and ATP generated by photosynthesis allows excess electrons to flow back through the quinone pool into the respiratory chain, where they are consumed to prevent the generation of harmful reactive oxygen species (ROS). It acts as a form of "flood control" and constitutes a vital photoprotective mechanism [517].

During Darkness or Low-Light Conditions

The respiratory chain operates independently, generating energy (ATP) by oxidizing organic substrates while electrons flow normally through the quinone pool. It even permits a process termed "chlororespiration", wherein respiratory chain components consume electrons from the photosynthetic chain in darkness.

The Relationship between Cyanobacteria and Quinones

Cyanobacteria were the first organisms to integrate quinone electron carriers into the photosynthetic chain. Quinones themselves are ancient lipid-soluble molecules, potentially present in prebiotic chemistry (evidenced in organic synthesis and meteorites), later incorporated by life into membrane electron transport systems. Evolutionarily, the shared "modules" (quinones+, cytochromes+, and iron-sulphur proteins) utilized by both respiratory and photosynthetic chains likely formed as early as the era of archaea. Cyanobacteria adapted this "module" for light-driven energy conversion, establishing a complete photosynthetic electron transport chain [517].

Summary

Quinones (such as plastid quinone) serve as a universal "electron and proton transporter" within cyanobacterial cells. Functioning like a bustling "traffic hub", it constitutes an obligatory pathway for both a series of photosynthetic reactions and a series of respiratory reactions [519]. This ingenious shared design enables cyanobacteria to regulate their energy metabolism with exceptional efficiency and flexibility according to environmental conditions (light, oxygen, nutrients), maximizing their survival advantage. Cyanobacteria =, the protagonists of the Great Oxygenation Event (GOE), are simply termed cyanobacteria in modern taxonomy. Quinone molecules serve as the common electron/proton carrier for both the respiratory and photosynthetic chains, shuttling electrons and protons across membranes. The photosynthetic chain of cyanobacteria employs plastoquinone (PQ), homologous to the ubiquinone (UQ) of the respiratory chain, indicating a shared evolutionary origin. It is analogous to the ubiquinone (UQ) in the mitochondrial respiratory chain, differing only in nomenclature but evolutionarily homologous. It provides molecular-level evidence for the evolutionary homology between photosynthesis and respiration.

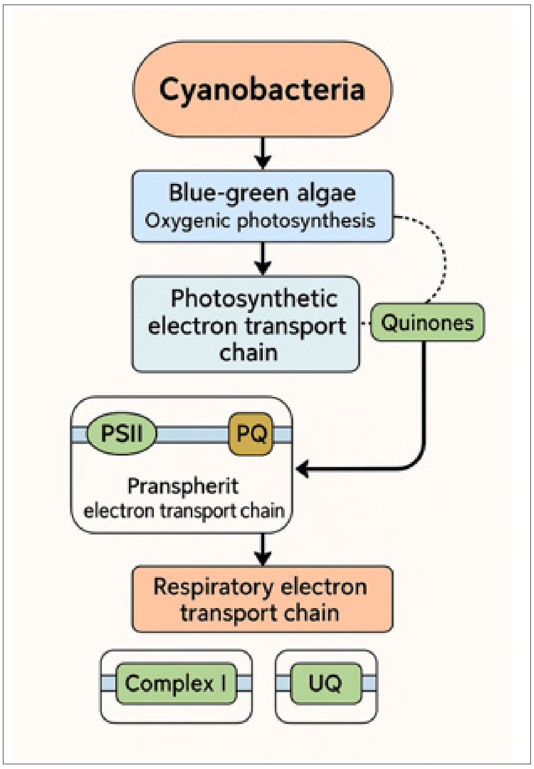

Figure 4: Photosystem II: The Reaction Centre of Oxygenic Photosynthesis

Evidence for the Great Oxygenation Event (GOE)

The Great Oxygenation Event (GOE) on Earth fundamentally altered the evolutionary history of life on our planet. It may be stated that without the Great Oxygenation Event, neither the Earth as we know it today, nor the life forms inhabiting it, including humankind, would exist. Whilst the chemical and molecular mechanisms of this event were examined in detail in preceding discussions, the precise timing of the Great Oxygenation Event (GOE) occurring 2.4 billion years ago remains subject to debate. Crucially, why are cyanobacteria, rather than other bacteria, identified as the primary agent responsible for the GOE? This question warrants detailed examination.

Geochemical Evidence for Atmospheric Oxygenation (Sulphur Isotope Anomalies) and the Origin and Distribution of Sulphur Isotopes in the Protoplanetary Disk:

Sulphur Isotope Anomalies as Evidence for Earth's Atmospheric Oxygenation Approximately 2.4 billion years ago (during the Great Oxygenation Event, GOE), a pronounced mass-independent fractionation (MIF-S) signal for sulphur isotopes emerged in Earth's rock strata [460]. MIF-S primarily manifests as deviations of $\delta^{33}S$ and $\delta^{36}S$ from mass-dependent relationships. It occurs because, in an anoxic atmosphere, ultraviolet photolysis of SO_2 produces distinctive sulphur isotope fractionation [520]. When sufficient free oxygen (O_2) appears in the atmosphere, SO_2 is rapidly oxidized to sulphate, suppressing this MIF signal. Consequently, the disappearance of MIF-S constitutes a geochemical "fingerprint" of atmospheric oxidation and cyanobacterial oxygen production.

Sulphur and Sulphur Isotopes in Protoplanetary Discs

Within protoplanetary discs, sulphur primarily exists as H_2S, SO_2, iron sulphide (FeS), sulphates, organothiophosphates, and other forms [521]. Sulphur isotopes (^{32}S, ^{33}S, ^{34}S, ^{36}S) within the disc are subject to: radioactive decay products (high-energy particles); ultraviolet/X-ray irradiation; and [522]. Meteorites (e.g., CI, CM, CV carbonaceous chondrites) preserve early protoplanetary sulphides and sulphates whose sulphur isotope compositions exhibit localized non-mass-dependent fractionation consistent with interstellar UV irradiation [453].

Connections and inferences: Protoplanetary disc → Earth's atmosphere

Premise Similarity

In the protoplanetary disc, ultraviolet radiation + fractionates SO_2 and H_2S; in the early Earth atmosphere, ultraviolet radiation fractionates SO_2 photolysis. The analogous mechanisms suggest the MIF-S signal is a universal product of ultraviolet photochemistry.

Continuity Hypothesis

Sulphur isotope anomalies → within the protoplanetary disc are preserved in planetesimals and meteorites; meteorite impacts introduced this isotopic signature to Earth →, where it superimposed upon the ultraviolet photolysis MIF from the early atmosphere; ultimately leaving sulphur isotope anomalies in Earth's sedimentary rock record.

Oxidation Tipping Point

When cyanobacterial oxygen production significantly increased, atmospheric O_2 accumulation → suppressed MIF-S formation; this shift is recorded in the sulphur isotope curve from 2.4 billion years ago. Thus, the sulphur isotope anomaly reflects both the early legacy of the protoplanetary disc and a turning point in Earth's atmospheric evolution.

The sulphur isotope anomaly in 2.4-billion-year-old strata constitutes an "internal signal" of revolutionary changes within Earth's own atmosphere-ocean system. In contrast, the sulphur isotope composition within the protoplanetary disc represents the "primordial background value" of the entire solar system's initial material. These two elements relate as "event" and "stage", rather than through direct causality.

The nature and significance of the 2.4-billion-year-old sulphur isotope anomaly (Earth's internal signal)

This anomaly is termed "Mass-Independent Fractionation" (MIF), typically denoted as $\Delta^{33}S$.

Principle

In a low-oxygen atmosphere, photochemical reactions triggered by ultraviolet (UV) photolysis of SO_2 gas produce a distinctive fractionation effect. This effect deviates from simple mass-dependent proportionality, causing the change in ^{33}S relative to ^{34}S to no longer precisely equal half the change in ^{32}S relative to ^{34}S. It generates the signal $\Delta^{33}S \neq 0$ [460].

Key Conditions

Absence of an ozone layer: Allows substantial ultraviolet radiation to reach the lower atmosphere. Absence of free oxygen (O_2): Enables SO_2 to persist and participate in photochemical reactions without being rapidly oxidized into sulphates.

Signal Preservation

Sulphur-containing species generated via MIF processes (such as elemental sulphur and sulphates) are sequentially deposited into oceans and sediments, ultimately becoming recorded within rock strata.

Signal Extinction

Rising atmospheric O_2 concentrations (the Great Oxygenation Event) led to ozone (O_3) formation, shielding the surface from ultraviolet radiation and terminating the photochemical reactions generating sulphur MIF. Subsequently deposited sulphides and sulphates exhibit $\Delta^{33}S$ values approaching zero [523].

Conclusion

The $\Delta^{33}S \neq 0$ signal in 2.4-billion-year-old strata serves as a "smoke alarm" confirming Earth's anoxic atmosphere devoid of ozone at that time. The subsequent $\Delta^{33}S \approx 0$ directly demonstrates the emergence of the ozone layer and the permanent rise of free oxygen.

The protoplanetary disc was the gaseous and dusty ring surrounding the young Sun during the early formation of the Solar System. Its sulphur isotope composition represents the initial state of the Solar System.

Origin

Planetary disc material inherits from the interstellar medium following previous stellar explosions, with its isotopic composition reflecting the blended results of various stellar nucleosynthesis processes across the Milky Way.

Characteristics

Analyses of the most primordial solar system material (such as meteorites, particularly carbonaceous chondrites) indicate that the solar system's primordial sulphur isotope composition was highly homogeneous, exhibiting no mass-dependent fractionation ($\Delta^{33}S \approx 0$). It implies that within the solar nebula, sulphur isotope fractionation was primarily driven by thermodynamic and kinetic processes, yielding mass-dependent fractionation (Mass-Dependent Fractionation), with a $\Delta^{33}S$ value of approximately zero.

Significance
This homogeneous $\Delta^{33}S \approx 0$ value is termed the "primordial solar system value" or "Canyon Diablo Troilite (CDT) standard", serving as the starting point for sulphur isotope evolution in all planetary bodies.

The Relationship Between Event and Setting: Unified Origin
Early Earth acquired material from the accreting protoplanetary disc, possessing an initial sulphur isotope composition that was also homogeneous with $\Delta^{33}S \approx 0$. Indeed, $\Delta^{33}S \approx 0$ signatures are observed in the oldest (>2.4 billion-year-old) sedimentary rocks, consistent with the characteristics of the protoplanetary disc.

Divergent Evolution
Following Earth's formation, its unique internal processes (particularly atmospheric chemistry) began to exert influence. Ultraviolet photochemical reactions within the anaerobic environment spontaneously generated $\Delta^{33}S \neq 0$ signatures within the Earth system. This signature constitutes Earth's distinctive "fingerprint," fundamentally distinct from the protoplanetary disc's initial state.

Signal Transition
The Great Oxygenation Event acted as a "system reset", halting MIF generation. Sulphur isotope records in sedimentary rocks reverted to $\Delta^{33}S \approx 0$. It did not signify a return to the protoplanetary disc state, but rather marked the Earth's atmosphere entering a wholly new, oxygenated evolutionary phase.

Analogy
The sulphur isotopes ($\Delta^{33}S \approx 0$) in planetary discs resemble a pristine white canvas (a uniform initial background). The early Earth's anoxic atmosphere acts like an artist, using ultraviolet radiation as a brush to create distinctive abstract patterns ($\Delta^{33}S \neq 0$) upon the canvas. The Great Oxygenation Event resembles a thorough repainting, covering the old patterns with oxygen and an ozone layer, restoring the canvas to pure white ($\Delta^{33}S \approx 0$). Yet this repainting itself marks the beginning of an entirely new historical phase [524].

Summary
Sulphur isotope anomalies (MIF-S) serve as geochemical markers of atmospheric oxidation. Similar fractionation mechanisms (UV irradiation, radiochemistry) existed within the protoplanetary disc, with meteorites preserving this record [461]. The relationship between the two may be understood as: Protoplanetary disc→ Meteorite sulphur anomalies (cosmic heritage); Early Earth → Atmospheric sulphur anomalies (biologically driven) [401]. Thus, sulphur isotope anomalies in Earth's atmosphere result from the combined effects of prebiotic cosmic legacies and oxygen production from cyanobacterial metabolism [461].

The sulphur isotope anomaly ($\Delta^{33}S \neq 0$) dating back 2.4 billion years is a product of Earth's own atmospheric processes, its origin being unrelated to the sulphur isotopic composition of the protoplanetary disc [525]. The disc's sulphur isotopes provided the initial conditions for evolution, while the anomalous signal on Earth records a revolutionary event occurring on our planet after deviating from these initial conditions.

At the core of the geochemistry-astrochemistry interface lies a classic case of "local signal versus global background": even a scientist might misinterpret it, perhaps constituting a paradox
In the previous section, the geochemical evidence for Earth's atmospheric oxidation (sulphur isotope anomaly) and the origin and distribution of sulphur isotopes in the protoplanetary disc appear unproblematic. However, I contend that the conclusions drawn are erroneous. Linking sulphur isotope mass-independent fractionation (S-MIF, expressed as $\Delta^{33}S$) with the evolution of the protoplanetary disc–meteorites–Earth's atmosphere provides a crucial clue and perspective for resolving this issue.

Review of Observational Facts
Planetary disc/meteorite stony-iron
Meteorites (including carbonaceous chondrites like Mochisen et al.) typically exhibit $\Delta^{33}S \approx 0$. It is because, within a vacuum-atmosphere-free solid environment, sulphur primarily originates from thermochemical/radioactive processes, following mass-dependent fractionation (MDF) and yielding no significant MIF signal.

Pre-Great Oxygenation Event (GOE) on Earth (~2.5 Ga ago)
Sediments exhibit $\Delta^{33}S \neq 0$ (marked MIF anomalies). It arises from an anoxic atmosphere where ultraviolet radiation irradiated SO_2, generating non-mass-dependent photochemical fractionation deposited within strata.

Post-Earth GOE (~2.4 Ga onwards)
Atmospheric O_2 levels rose, the ozone layer formed, ultraviolet radiation was shielded, the S-MIF signal vanished, and $\Delta^{33}S$ returned to ≈ 0. It aligns with the background state of meteorites exhibiting $\Delta^{33}S \approx 0$.

Comparative Relationships
Planetary disc bodies ($\Delta^{33}S \approx 0$); Earth pre-GOE ($\Delta^{33}S \neq 0$); Earth post-GOE ($\Delta^{33}S \approx 0$, consistent with meteorites).

What does this indicate?
The Uniqueness of Earth's Early Atmosphere
The pre-GOE anomaly of $\Delta^{33}S \neq 0$ indicates this was a product of atmospheric photochemistry, not the protoplanetary disc background. In other words, the MIF signal only emerges under Earth's distinctive reducing atmospheric conditions.

The GOE Restored Earth's Atmosphere to a 'Planetesimal Background'
Post-GOE $\Delta^{33}S \approx 0$, matching planetary disc planetesimals/meteorites, indicating Earth's atmosphere entered an oxidized steady state where atmospheric–lithospheric cycles converged with the isotopic state of solar nebular solids [523].

Significance of Radiative-Metabolic Co-Evolution
Before the GOE, life and the atmosphere coexisted within a highly non-equilibrium chemical environment driven by radiation and ultraviolet radiation. Post-GOE, with O_2 accumulation, environmental chemistry stabilized ($\Delta^{33}S \approx 0$), aligning with the baseline state of meteorites/planetesimals. Life subsequently evolved over extended periods under chemical conditions closer to the "planetary disc background". It suggests that Earth only truly aligned with its protoplanetary disc heritage after the GOE, establishing the backdrop for eukaryotic life's emergence.

Summary
Planetary disc planetesimals $\Delta^{33}S \approx 0$ → represent the

"background" of mass-dependent fractionation. Earth pre-GOE $\Delta^{33}S \neq 0$ → unique signal from the reducing atmosphere and ultraviolet photochemistry. Post-GOE Earth $\Delta^{33}S \approx 0$ → aligns with protoplanetary disc meteorites, indicating oxygen shielded UV radiation and stabilized the environment. This demonstrates: the GOE represents an atmospheric chemical inflection point of "return to the nebular background", marking the entry of life and environment into a long-term stable co-evolutionary phase [461].

Sulphur isotope anomalies and the GOE: Evidence for Earth's atmospheric return to nebular background

Planetesimals formed within the protoplanetary disc were subjected to prolonged exposure to radiation-driven processes and radiochemical interactions. The decay of short-lived nuclides (such as ^{26}Al and ^{60}Fe) released high-energy particles and radiation, whilst long-lived nuclides (such as ^{238}U, ^{232}Th, and ^{40}K) provided a low-dose, sustained energy input. This combination established a stable radiochemical-oxidative environment within the planetesimal's interior and surface. Within this environment, the sulphur isotope system generally exhibits $\Delta^{33}S \approx 0$, indicating mass-dependent fractionation (MDF), without showing the mass-independent fractionation (MIF) characteristic of atmospheric photochemical processes.

In stark contrast, Earth's pre-Great Oxygenation Event (GOE, >2.5 Ga) atmospheric conditions were highly reducing, lacking persistent oxygen shielding. Ultraviolet radiation penetrated deeply into the atmosphere, driving SO_2 photolysis and generating a pronounced MIF signal with $\Delta^{33}S \neq 0$. This anomaly provides crucial geochemical evidence for early atmospheric anoxia [460].

Upon the onset of the Great Oxygenation Event (GOE, ~2.4 Ga), atmospheric oxygen levels rose markedly, an ozone layer formed, ultraviolet radiation was shielded, the S-MIF signal vanished, and $\Delta^{33}S$ returned to ≈0 [523]. It signifies that Earth's atmosphere transitioned post-GOE from a unique "reduction+UV-driven" system to an oxidation-stable state consistent with a planetoid radiation–oxidizing environment [526].

Notably, cyanobacteria played a pivotal role in this transition. As microbial relics from the protoplanetary disc–planetesimal phase, cyanobacteria had already evolved radiation-resistant and antioxidant mechanisms under radioactive conditions, conferring metabolic advantages for tolerating and utilizing oxidizing environments. Upon arrival on Earth via meteorites or early planetesimal material, their oxygen-producing photosynthesis decomposed water, gradually depleting CO_2 and releasing O_2, thereby driving the Earth's atmosphere from a CO_2-N_2 dominance towards an O_2-N_2 dominance. This process effectively "restored" the Earth's atmosphere to the oxidative baseline state characteristic of the planetesimal radiation environment.

Thus, the evolutionary trajectory of sulphur isotope anomalies ($\Delta^{33}S \neq 0 \rightarrow \Delta^{33}S \approx 0$) not only provides direct evidence for the GOE but also suggests that the radiative–oxidative environment within protoplanetary disks shares chemical homogeneity with the post-GOE Earth environment [459]. Cyanobacterial oxygen production served as the biological driving force for this "reversion"; life not only adapted to the radiative-metabolic backdrop of the protoplanetary disc but also extended this legacy into the terrestrial environment, propelling the co-evolution of atmosphere and life.

The Radiation–Metabolism Framework and the Evolution of Early Life Systems

The preceding discussion has revealed the dual role of radioactive isotopes within protoplanetary discs and planetesimals: short-lived radionuclides (SLRs) catalyze prebiotic chemical reactions, whilst long-lived radionuclides (LLRs) sustain a persistent energy background. This radiometabolic framework not only shaped the synthetic environment for organic molecules but also, through radiochemistry and mineral-water interactions, established the foundations for early life's energy utilization. It likewise laid the groundwork for the emergence and evolution of life within planetesimals. As these life forms, such as bacteria, were delivered to Earth alongside energy via meteorites, they became the 'heritage' of our planet's earliest metabolic and evolutionary systems.

During Earth's early evolution, life did not emerge directly as complex eukaryotic systems but underwent a multistage transition: from prokaryotic metabolic networks→, cyanobacterial oxygen-producing metabolism→, and the emergence of eukaryotic cells [527]. Within this chain, the radiation-metabolism framework not only provided energy sources but also shaped life's long-term adaptive mechanisms for radiation, oxidative stress, and electron flow utilization.

Cyanobacteria and Radiation–Metabolism Coevolution

Cyanobacteria represent pivotal inheritors within the radiation–metabolism framework. They evolved oxygenic photosynthesis, utilizing photons and water as electron donors to release O_2, thereby directly altering Earth's atmospheric composition (the Great Oxygenation Event, GOE) [528].

Possessing robust radiation-resistant and antioxidant mechanisms, they exhibit adaptive traits highly consistent with radiation-driven environments. The quinone electron carriers (PQ, UQ) in the photosynthetic chain and the ubiquinone/cytochrome complexes in the respiratory chain structurally and functionally perpetuate the early radiation-electron flow mechanism. Thus, cyanobacteria are not only catalysts of atmospheric transformation but also vivid embodiments of radiation-metabolism co-evolution extending from the starlite phase to Earth's biosphere.

Prokaryote–Eukaryote Transition

The massive O_2 released by cyanobacteria altered environmental selection pressures, enabling oxidative respiratory chains to supplant earlier anaerobic metabolism and propel eukaryotic cell emergence gradually. The respiratory chain within mitochondria bears a striking resemblance to cyanobacterial photosynthetic chains, suggesting eukaryotic energy metabolism directly inherits from the prokaryotic cyanobacterial–archaea system [529]. The radiation–metabolism framework manifested in this transition as follows: persistent radiation drove DNA repair and antioxidant evolution; O_2 accumulation propelled more energy-efficient metabolic patterns; metabolic complexity provided conditions for intracellular symbiosis and eukaryotic evolution [530].

In summary, cyanobacteria represent the 'biological' phase of radiation–metabolism co-evolution; how the radioactive background shaped life's radiation resistance–antioxidant–electron flow utilization mechanisms; and how the transition from prokaryotes to eukaryotes reflects the continuity of the radiation–metabolism framework [531].

Emergence of Eukaryotes and the Great Oxygenation Event (GOE)

Temporal Framework

Great Oxygenation Event (~2.4–2.3 Ga): Atmospheric O_2 concentrations rose markedly, the sulphur isotope MIF signal vanished, and banded iron formations (BIFs) decreased in deposition, marking the transition from a reducing to an oxygenated environment [523]. Earliest fossil evidence for eukaryotes (~1.8–1.6 Ga): Includes acritarchs and eukaryote-like microfossils, suggesting eukaryotes emerged hundreds of millions of years after the GOE [532]. Molecular clock estimates: Some studies propose eukaryotic cells may have originated around ~2.2–2.0 Ga, but only diversified significantly around ~1.6 Ga [533].

Significance of the GOE for eukaryotic origins

Oxygen as a Metabolic Prerequisite

The core characteristic of eukaryotes is the possession of mitochondria, whose respiratory chain relies on O_2 as the terminal electron acceptor. Without atmospheric oxidation, the evolution of complex aerobic respiration would have been difficult to stabilize.

Oxidative Stress and Cellular Defence

The GOE presented a double-edged environmental challenge: O_2 fuelled high-energy metabolism, supporting genomic expansion and cellular complexity. Yet O_2-generated ROS (reactive oxygen species) exerted intense selective pressure, driving the evolution of DNA repair and antioxidant mechanisms.

Symbiotic Theory and Oxygen Background

The most compelling explanation for eukaryotic origins is the endosymbiotic theory: archaeal hosts engulfed cyanobacteria or α-proteobacteria, which evolved into mitochondria. Post-GOE, oxygen-rich environments conferred selective advantages to this symbiosis, establishing aerobic respiration as the dominant paradigm [527].

Evolutionary Sequence

Pre-GOE: Archaea and bacteria dominated, primarily employing anaerobic metabolism (methane production, sulphide metabolism, iron reduction). Post-GOE: O_2 accumulation, Altered redox environment, Establishment of stable aerobic respiratory chains, Facilitated emergence of eukaryotes. Conclusion: The origin of eukaryotes is intrinsically linked to the oxygenated environment following the GOE. At the very least, the GOE represents a temporal precondition, providing the metabolic and environmental backdrop for eukaryotic emergence.

Summary

The Great Oxygenation Event (~2.4 Ga) preceded the emergence of eukaryotes (~1.8–1.6 Ga). Atmospheric oxygenation provided essential conditions for eukaryotic energy metabolism (mitochondria), genomic complexity, and cellular symbiosis. Thus, eukaryotes may be regarded as the continuation and deepening of radiometabolic co-evolution following the GOE, representing a direct outcome of oxygen accumulation.

Origin of Eukaryotes and Radiation–Metabolic Coevolution

During the protoplanetary disc phase, bacteria and archaea already existed within a high-radiation background environment [534]. The intense radiation from short-lived nuclides (such as ^{26}Al, ^{60}Fe) and the sustained energy release from long-lived nuclides (such as ^{238}U, ^{232}Th, ^{40}K) compelled their metabolic systems to endure prolonged radiation stress and oxidative stress [259]. Consequently, within the protoplanetary disc environment, microbial communities progressively established radiation–metabolism coupling mechanisms: harnessing radiation-driven radical chemistry via electron transport chains; countering oxidative stress through antioxidant enzymes and DNA repair systems; and developing tolerance to ROS (reactive oxygen species) and radiation damage [535,458].

This radiation–metabolism coevolutionary legacy, forged within the protoplanetary disc, was carried to Earth by early life.

When the Great Oxygenation Event (GOE, ~2.4 Ga) occurred, atmospheric and oceanic O_2 concentrations rose dramatically. For life, this represented a profound environmental shift [523]. Yet, having already evolved antioxidant and anti-radiation mechanisms within the protoplanetary disc, bacteria and archaea not only adapted to this oxidative stress but also gained the metabolic foundation for further oxygen utilization [461].

Against this backdrop, certain prokaryotic archaeal hosts underwent endosymbiosis with bacteria (particularly the α-proteobacteria group): bacteria entered the archaeal host cell and gradually evolved into mitochondria [529]. Mitochondria inherited the bacterial electron transport chain and aerobic respiration function, thereby endowing the nascent eukaryotes with highly efficient energy metabolism capabilities [532]. This turning point demonstrates that the evolutionary trajectory from bacteria/archaea to eukaryotes did not commence from scratch, but rather built upon antioxidant adaptations within the planetary disc's radiation–metabolism context. While prokaryotic bacteria and archaea themselves lacked mitochondria, their prolonged radiation–metabolism adaptations transformed them into “energy organelles” within eukaryotic cells, facilitating eukaryotic flourishing in oxygen-rich environments [531].

Thus, the emergence of eukaryotic life may be viewed as the continuation and sublimation of radiation-metabolism co-evolution: from radiation-antioxidant mechanisms within the protoplanetary disc to the integration of aerobic metabolism post-GOE, life continually transformed the cosmic radiation legacy into increasingly complex biological energy systems. From the foregoing discussion, we arrive at the final conclusion: “radiation-metabolism co-evolution→ altered atmospheric conditions → efficient aerobic metabolism in eukaryotes”.

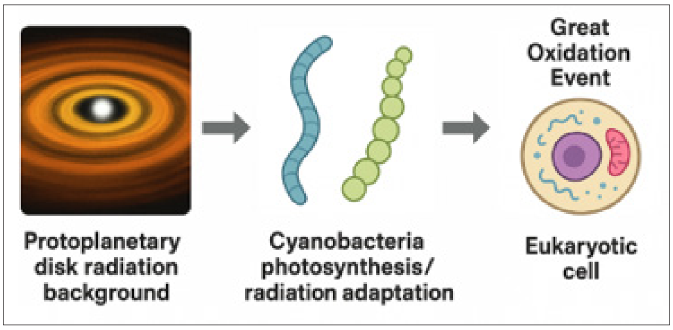

Figure 5: The Evolutionary Process from Protoplanetary and Planetary Disks, Via Cyanobacteria-Mediated GOE, to Eukaryotic Cellular Life

The internal environment of planetesimals in protoplanetary disks is entirely different from that of planetesimals in planetary disks.

Because planetesimals in the protoplanetary disk are relatively small, they constantly collide with other planetesimals and are influenced by the disk's reducing atmosphere. It leads to a constant exchange of material between planetesimals and the surrounding disk atmosphere, as well as other planetesimal material. Due to the influence of the protoplanetary disk's reducing atmosphere, planetesimals are relatively small, and viscous collisions between them make them highly permeable. In other words, the interiors of planetesimals in the protoplanetary disk are in a reducing state, controlled by the disk's reducing atmosphere. After 5-10 million years of evolution, protocells should have formed [531].

within the planetesimals within the protoplanetary disk. The central law of protein translation in the entire galactic disk must have been established and agreed upon through the interactions and collisions between planetesimals. Even after the protoplanetary disk's reducing atmosphere is dissipated and depleted, or in the early stages of the disk, even without a protoplanetary atmosphere, material exchange between planetesimals continues. The central law of protein translation in protocells should have been established and agreed upon in planetesimals in the early stages of the disk. Cells continued to evolve within the planetesimals within the planetary disk. As the planetesimals within the disk gradually grew larger and the reducing atmosphere of the protoplanetary disk was depleted, the exchange of matter between the planetesimals within the disk decreased. The interiors of the planetesimals in the disk were heated by solar radiation and the short- and long-lived isotopes within the planetesimals. Radiolysis also produced nutrients and byproducts such as superoxide ions, which are necessary for protocell evolution. It nourished the evolving bacteria while also developing radiation and antioxidant resistance. Therefore, the internal environment of the planetesimals within the planetary disk was oxidizing. That is, the internal environment of the planetesimals in the protoplanetary disk was reducing, while that of the planetesimals in the planetary disk was oxidizing. Later in the evolution of the planetary disk, the communication between planetesimals decreased, possibly due to the differentiation of bacteria or viruses within each planetesimal. Because the radioactivity of radioactive isotopes within different planetesimals varied, the resulting bacteria also had varying radiation resistance.

The Origin and Evolution of Life

We have analyzed the entire process from the origin of life in the protoplanetary disc to its evolution within planetary disc planetesimals through prebiotic chemistry. The conclusions drawn from this analysis unequivocally indicate that the origin of life and the vast majority of its evolution—including the establishment of cellular metabolic networks, the formation of cell membranes and cell walls, and the completion of the entire process of establishing the cellular genetic system and its transcription and translation—all occurred within the protoplanetary disc and planetary disc planetesimals. Moreover, viruses and bacteria developed comprehensive defence systems in response to the radiation of radioactive isotopes and the generation of oxidizing molecules within planetary disc planetesimals. These life forms, including bacteria and viruses, merely underwent adaptation to Earth's environment and further evolution tailored to terrestrial conditions after being delivered via meteorite impacts. However, without the complete life systems constructed within protoplanetary disks, these organisms could not have adapted or evolved upon reaching Earth. This paper repeatedly refutes the "Miller–Urey experiment", which is founded upon the theoretical basis of the "Oberlin–Haldane hypothesis" [3,2]. By elucidating metabolic primacy, it refutes the "RNA World Hypothesis" [4]. Furthermore, the "Hydrothermal Vent Theory" further strains to identify an environment on Earth where life could have arisen, yet its metabolic systems and survival conditions remain logically inconsistent [5]. Thus, we arrive at a definitive conclusion—one I established in last year's paper and reiterated at —that life originated within the protoplanetary disc [10]. It underwent hundreds of millions to billions of years of evolution within planetesimals. Whether bacteria or viruses splashed onto Earth from these planetesimals, they profoundly and subtly shaped terrestrial life. Examples include the Cambrian explosion and Earth's mammals, where numerous endogenous retroviral elements in the human genome may have been "domesticated" by their hosts, allowing them to evolve new cellular functions [536]. For instance, the syncytin protein ( ), crucial for placental formation, derives from ancient viral genes [537]. Approximately 8% of the human genome consists of retroviral gene fragments, vividly illustrating the intricate relationship between viruses and mammals, including humans.

In my previous article, "Chemical Analysis of Life Origins in the Protoplanetary Disc," Darwin's Tree of Life represents a trunk, with its roots embedded in the protoplanetary disc. Through the progressive analysis and research presented in this article, I have arrived at a new conclusion. That is, the root system of the Tree of Life lies within the protoplanetary disc and its planetary bodies, and the countless bodies orbiting within the Solar System's orbital plane may each represent a small system for the birth of life. It raises the question: do all these small bodies ultimately generate the same metabolic networks, cell membranes, and genetic systems, all adhering to the same central dogma translation system? It necessitates understanding how protoplanetary bodies interact within the orbits of the protoplanetary disc or planetary disc. Each small protoplanetary body, whether on its surface or internally, likely lacks the capacity to establish a complete metabolic system, cell membrane, or genetic system. Collisions between these small bodies within their orbital paths could be elastic; they could be rigid, resulting in fragmentation; or more likely, viscous, facilitating mutual exchange of matter. Planetesimals may grow progressively larger through viscous collisions. A complete metabolic system, membrane system, and genetic system could ultimately be established among the planetesimals orbiting the solar system through collisions and the exchange of matter and prebiotic chemicals between them.

Given the abundance of protoplanetary bodies within the solar system's protoplanetary disc and planetary disc, the cyclical process of collision, fragmentation, collision, and adhesion – this repeated 'exchange' – proves crucial. It constitutes the key to establishing a unified central dogma of protein translation. Regardless of differing cellular metabolic pathways or variations in cell membrane and cell wall structures (which vary according to the internal environment, metabolism, and membrane/wall composition of distinct protoplanetary bodies), the outcomes converge. The central dogma of protein translation remains universally consistent. Thus, the establishment of this dogma constitutes the foundational junction where the roots and trunk of the evolutionary tree of life converge. We may further explore the roots branching out in various directions, representing metabolic networks arising from differing environments among distinct asteroids. These metabolic networks may also possess genetic systems, which are manifested through specific genes.

This analysis raises a pertinent question: both the roots and trunk of the Tree of Life—or at least its lower trunk—originated within planetary disc protoplanets. We can reasonably assert that life evolved within these protoplanetary discs for approximately 500 million years, or possibly even longer, until the "Heavy Bombardment Period," when certain life forms—such as bacteria and viruses—were transferred to Earth via meteorites. Following their arrival on Earth, these bacteria and viruses underwent a protracted process of adaptation and evolution. It established a substantial portion of the branches of the Tree of Life. According to the theory of life's origin and evolution from the protoplanetary disc and planetary disc particles, these particles were continuously introduced to Earth via meteorites from the disc. Consequently, regarding the latter half of Earth's Tree of Life—comprising its branches and leaves—we remain uncertain to what extent it continues to be influenced by bacteria and viruses originating from planetary disc particles. It must be recognized that while Earth's Tree of Life evolves, so too does the life within planetary disc particles. In truth, the life within planetary disc particles and the life on Earth form a single Tree of Life, albeit one whose roots and trunk reside within the planetary disc. To say that life within planetary disks evolves under environmental influences is akin to stating that life on Earth is shaped by the environments of the Milky Way and the Solar System. Both are subject to environmental pressures that alter their evolutionary trajectories. The sole distinction lies in the fact that life on Earth remains continuously influenced by the life within planetary disks. As this life within the disks continually evolves, we cannot ascertain the extent to which, during different periods of the past, this life within the planetary disks has impacted life on our planet.

Regarding the Tree of Life, we may depict it thus: its roots lie within the protoplanetary disc. The trunk of the Tree of Life, which does not represent any single organism, symbolizes the central dogma of the protein translation system, also situated upon the planetary disc. From this trunk, two branches diverged upon the planetary disc: Bacteria and Archaea. Subsequently, portions of both Bacteria and Archaea arrived upon Earth. From the Archaea lineage emerged the eukaryotic cell category, which inhabited Earth. Eukaryotic cells then differentiated into all subsequent higher life forms, including humankind. Bacteria, archaea, and viruses from the planetary disc's celestial bodies continuously descended onto Earth. That is, these entities from the disc's celestial bodies continually entered the branches and leaves of Earth's evolutionary tree. Meanwhile, bacteria, archaea, and viruses within the disc's celestial bodies continued to evolve within the disc itself, influencing the evolution of life forms on Earth. Conversely, the evolution of life on Earth did not affect the evolution of life within the planetary disc.

It is worth emphasizing that what is described here is life originating and evolving within the protoplanetary disc of the Solar System and within the protoplanetary discs of other stars. It has no connection to other stellar systems or galaxies. The material composition of the Solar System's protoplanetary disc benefited from the supernova explosions and AGB stars present in its surrounding environment at the time of its formation, as well as the substantial material generated by the protoplanetary discs of other nascent stars. It endowed the Solar System with an abundance of "exogenous input" rich in substances conducive to the emergence of life during its infancy. However, these materials did not include the crucial precursors for the emergence of life, such as amino acids, nucleic acids, and fatty acids. These substances must have been synthesized within the Solar System's protoplanetary disc itself – a process termed "endogenous synthesis". It fundamentally differs from the prevailing theories of life's origin, which describe a dual process of "exogenous input and endogenous synthesis". The former describes the environment of the molecular cloud preceding the formation of the Solar System's protoplanetary disc, and the endogenous synthesis environment within that disc. The latter, embraced by contemporary mainstream origin-of-life scholars, posits that prebiotic chemical substances were delivered to Earth from extraterrestrial bodies—via meteorites or comets—serving as the nutrient base for the emergence of life on Earth. Earth itself, then, is the site of life's "endogenous synthesis". Through a detailed analysis of the entire article's arguments and evidence, I have thoroughly refuted the hypothesis of Earth's origin of life. I contend that life originated within the protoplanetary disc, undergoing hundreds of millions of years of evolution within this environment before being ejected onto Earth. Here, it began adapting to terrestrial conditions and continued to evolve. Simultaneously, life forms remaining within the protoplanetary disc continued their own evolutionary trajectory.

Conclusion

This paper examines the four most critical and contentious domains of life's genesis by analyzing the birth process centred on the protoplanetary disc. These domains comprise:

- Geological environment;
- Source of nutrients/initial molecules;
- Source of energy;
- The division between the RNA world and the metabolic world first occurred. To date, scientists have reached no consensus on these questions.

In terms of geological conditions, this paper emphasizes that protoplanetary discs inherit the legacy of Type II supernovae, asymptotic giant branch (AGB) stellar winds, and binary neutron star mergers. It endows protoplanetary disc dust with exceptionally high metallicity, a carbon-rich environment, and rare heavy elements, including radioactive metals. The diverse environments within the protoplanetary disc—including the inner disc, mid-disc, snow line, and outer disc—along with the exchange of dust and gas between these zones, provide an exceptional reaction platform for prebiotic chemistry. These crucial environments for life's origin do not exist on Earth.

Regarding the origin of food/initiating molecules, this paper emphasizes that the protoplanetary disc—the circumstellar gas and dust disc formed during star formation—serves as a crucial transitional stage linking interstellar matter with the chemical potential for life. This paper underscores the vital role of transition metals, short- and long-lived radioactive isotopes, PAHs, fullerenes, and the metal-organic compounds formed from these substances in life's composition. On Earth, these materials are either exceedingly rare or cannot exist independently; instead, they are embedded within rocks, offering no assistance to life's emergence or evolution. Analysis of meteorites further reinforces the credibility of the protoplanetary disc as the origin of life. It describes how life progressively evolved from simple molecules through various chemical reactions to form prebiotic compounds such as amino acids, ribose, and fatty acids. The paper highlights the significance of hemolithin discovered in meteorites and the potential crucial influence of quantum mechanics on life's emergence within the protoplanetary disc. Crucially, these vital chemical and prebiotic reactions would have been nearly impossible to achieve on Earth. Regarding energy sources, this paper emphasizes that the energy required for life's emergence is quantifiable. The energy driving life's origin and evolution within protoplanetary and planetary discs can be summarised by $F=ma$ and $\Delta E = \Delta m \times c^2$. These energy sources derive not only from the kinetic energy of the protoplanetary disc, expressed by F=ma, but also from the conversion of this kinetic energy into chemical reactions, ultimately yielding prebiotic effects. Furthermore, the energy generated by radiation from the decay of radioactive isotopes within the protoplanetary and planetary discs, alongside the energy produced by solar nuclear fusion, can be expressed by the formula $\Delta E = \Delta m \times c^2$. This energy does not merely generate heat; crucially, it produces radiolysis effects through solar radiation, cosmic rays, and isotopic decay. These effects facilitate prebiotic chemical reactions and provide sustenance for life within the protoplanetary disc. The energy mentioned above and the resulting chemical reactions would be extremely weak or entirely absent on Earth.

Regarding the RNA World versus Metabolism First debate, this paper emphasizes the Metabolism First theory. It is demonstrated through the high concentrations of PAHs and fullerenes in protoplanetary discs, and the influence of these molecules on the formation of aromatic amino acids and aromatic hydrophobic proteins, which in turn affect the chirality of nucleic acid molecules. Furthermore, the discovery of haemolithin and its impact on RNA synthesis reinforces the theoretical framework of "metabolism preceding ." However, neither the emergence of the "RNA world" nor the potential chiral induction of nucleic acids by aromatic hydrophobic proteins and fullerenes could have occurred on Earth.

Beyond resolving these four most contentious issues among contemporary scientists, this paper also addresses two crucial questions concerning life's origins. These pertain to the establishment of the trinity comprising metabolic networks, cell membrane systems, and genetic systems. It further explores the evolution of life from its inception within protoplanetary discs to its progression within planetary disc planetesimals. The discussion examines how life was constructed within protoplanetary and planetary discs, and how these life forms subsequently evolved.

The completion of the tripartite architecture of metabolism, encapsulation, and heredity in protoplanetary disc life is examined. Beginning with haemolithin and the origins of primitive metabolic systems, the paper explores the triple functionality of such metal-coordinating proteins and the subsequent internal functional mechanisms they engendered. Furthermore, it introduces how this protein laid the chemical groundwork for establishing the "RNA world" of informational molecular assembly. The light-driven hydrolysis, metabolic electron transfer, and dehydration capabilities provided by haemolithin, combined with spontaneously formed lipid vesicle structures within protoplanetary or interstellar environments, enabled the gradual construction of primitive cells possessing the tripartite elements of "metabolism–boundary–stability". Within protoplanetary disc planetesimals, lipid vesicles encapsulating metabolic small molecules and informational polymers, sustained by external energy sources, gradually evolve into primordial systems possessing the tripartite functions of "replication–metabolism–boundary". Subsequently, the integration of energy, protein metabolism, and membrane–genetic systems occurs within the protoplanetary disc. Ultimately, a "self-maintaining and self-replicating cycle" system is established within the protoplanetary disc.

Finally, and crucially, this article discusses how life is constructed within protoplanetary and planetary discs, and how such life evolves. It elucidates the continuity and consistency over hundreds of millions of years of the gaseous and molecular dust composition within protoplanetary discs, alongside the gases and molecules that can form within planetary discs. It provides a stable energy source and an excellent sanctuary for the emergence of life within protoplanetary discs and its subsequent evolution within planetary disc bodies. Earth, however, could not possibly possess an environment and conditions identical to those of a protoplanetary disc or planetary disc. The philosophical coherence that wherever gases and molecules exist, life ought to emerge is elucidated. It demonstrates the consistency between the gases and molecules present in the protoplanetary disc (such as H_2, CO, CO_2) and those obtainable within planetary disc planetesimals, alongside the electrons associated with them. The bacteria consuming these gases and molecules are consistently found alongside them within the planetesimals of the planetary disc. These gases and molecules are generated within planetary disc protoplanets by radioactive isotopes (such as ^{60}F, ^{238}U, ^{40}K), simultaneously producing oxygen radicals and hydrogen peroxide (e.g., H_2O_2, $\bullet OH$, $O_2^{\bullet -}$, NO_3^-). Thus, isotopes provided both energy for bacterial survival and nutrients for bacterial metabolism, while simultaneously generating oxygen-free radicals and hydrogen peroxide that constituted harm to these bacteria. Consequently, bacteria acquired the nutrients required for their metabolism while simultaneously developing the capacity to resist oxygen-free radicals and hydrogen peroxide. It constitutes the core of this article: the "radiation-metabolism coupling" and "radiation-metabolism co-evolution" hypotheses for the origin of life in protoplanetary and planetary disks. Within this theoretical framework, the model of "radiation-metabolism co-evolution" in the origin of life is elaborated. It posits the long-term coexistence of radiation-generated gases and molecules with bacterial metabolism and antioxidant functions. This "radiation-metabolism co-evolution" hypothesis alone can explain the survival characteristics exhibited by all bacteria and viruses observed today. The fundamental logic underpinning why bacteria, archaea, and viruses exhibit exponentially greater radiation resistance than mammals lies in the direct consequence of these microorganisms coexisting with radiation within planetary disc protoplanets over extended periods.

Evidence from Murchison and other meteorites, where abundances of short-lived radioactive isotopes (SLRs) and long-lived radioactive isotopes (LLRs) markedly exceed those in Earth's crust, underscores the central tenet of "radiation-metabolism co-evolution". Research on the Great Oxygenation Event (GOE) demonstrates that this event, dominated by cyanobacteria, represents a consistent progression from "radiation-metabolism coupling" and "radiation-metabolism co-evolution" to radiation-metabolism-atmosphere environmental change. Comparing sulphur isotope mass-independent fractionation (S-MIF, $\Delta 33S$) data from pre- and post-GOE Earth with protoplanetary disc samples reveals that the GOE effectively restored Earth's S-MIF state to the oxidized conditions prevailing in the protoplanetary disc. It further demonstrates that bacteria migrating from the protoplanetary disc to Earth transformed the planetary atmosphere into the oxidized habitat they inhabited within the disc – the very environment sustaining our existence today. Finally, it is discussed that the highly efficient aerobic metabolism of eukaryotes is also directly descended from the antioxidant bacteria of the protoplanetary disc. This article further explores the principles potentially underlying the 'central dogma' of protein translation. It also highlights the potential connection between the antioxidant mechanisms and genes of birds and octopuses migrating along Earth's magnetic field lines and those of bacteria.

The paper concludes by constructing a novel Tree of Life, demonstrating that the evolutionary tree of life differs entirely from our currently accepted model. The roots and trunk of this evolutionary tree are not on Earth, but on the planetary disc. Its two branches – bacteria and archaea diverge, with archaea giving rise to a branch of eukaryotes, constituting our primary terrestrial life today. Bacteria, archaea, and viruses continue to evolve both on the planetary disc and on Earth, exerting influence upon the evolving terrestrial tree of life.

Future and Outlook

In our quest to understand life's origins, humanity has spared no effort, conceiving as many possible pathways as conceivable. This paper proposes novel hypotheses regarding life's origin: the 'radiation-metabolism coupling' and 'radiation-metabolism co-evolution' hypotheses concerning life's emergence in protoplanetary and planetary disks, alongside the 'radiation-metabolism co-evolution-alteration of atmospheric conditions-eukaryotic efficient aerobic metabolism' hypothesis. It is hoped that an increasing number of scientists, through solar system archaeology and the exploration of distant stellar protoplanetary discs, will gain deeper insights into the physicochemical mechanisms and phenomena within protoplanetary discs. It may ultimately unravel the mysteries of life's origins.

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