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Cosmic-Ray-Driven Bioenergetic Mechanism Postprint

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Abstract

According to models such as panspermia theory or the nebular relay hypothesis, the ancestors of life on Earth may have once resided in molecular clouds. What, then, were the energy sources and bioenergetic mechanisms of these organisms? A bioenergetic mechanism is proposed in which cosmic rays ionize hydrogen molecules to provide energy, which may be related to chemiosmotic theory or may constitute its origin. Based on this mechanism, it is suggested that the Last Universal Common Ancestor was an organism that utilized hydrogen molecules as donors for the electron transport chain.

Full Text

Preamble

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Cosmic Ray-driven Bioenergetics for Life in Molecular Clouds

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ABSTRACT

According to models such as panspermia or the Nebula-Relay hypothesis, the ancestors of life on Earth once lived in molecular clouds. What, then, are the energy sources and bioenergetic mechanisms for such lifeforms? This paper proposes a novel bioenergetic mechanism powered by cosmic ray ionization of

hydrogen molecules and discusses its relationship with the origin of chemiosmosis. Based on this mechanism, the Last Universal Common Ancestor may have been a lifeform that utilized hydrogen molecules as donors for electron transport chains.

Key words: astrobiology, astrochemistry, interstellar medium (ISM), nebulae, cosmic ray

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Introduction

Life's genetic and biological activities depend fundamentally on bioenergetics, which governs energy flow in living systems. These processes include energy transformation and the production and utilization of adenosine triphosphate (ATP) molecules, effectively converting chemical energy into ATP that is essential for life. On Earth, cellular respiration occurs through two primary pathways: aerobic and anaerobic respiration. In 1961, Peter D. Mitchell proposed the chemiosmotic theory [?], demonstrating that ATP synthesis is driven by an electrochemical gradient established across the plasma membrane as hydrogen ions (protons) diffuse from regions of high concentration to low concentration. The energy released through the electron transport chain maintains this proton concentration gradient via a proton pump mechanism.

According to models such as panspermia and the Nebula-Relay hypothesis [?], the ancestors of Earth's life may have originated in the Sun's predecessor planetary system and lived in the pre-solar nebula—a molecular cloud where the solar system formed. The Nebula-Relay hypothesis suggests that life in the solar system originated on a planet of the Sun's predecessor star through complex physicochemical interactions similar to abiogenesis on Earth [?, ?]. These primitive organisms then populated the pre-solar nebula created after the predecessor star's death. Unlike the panspermia theory [?], this model predicts that homologous lifeforms or their fossils could be found throughout the solar system. Previous work [?] has shown that the ultra-low temperature environment of molecular clouds might explain the origin of chirality in biological molecules.

How would life obtain sufficient energy in molecular clouds? What bioenergetic mechanisms would support life in such environments? As proposed in Ref. [?], cosmic rays (CR) represent the primary energy input for molecular clouds and may also serve as the energy source for life there. CR particles possess substantial energy, and their collisions with molecules in molecular clouds induce the production of lower-energy particles, thereby reducing potential damage from high-energy radiation. This paper proposes a novel bioenergetic mechanism driven by CR ionization of hydrogen in molecular clouds. Notably, this scenario applies to all potential lifeforms in molecular clouds, not only those hypothesized by panspermia or the Nebula-Relay hypothesis.

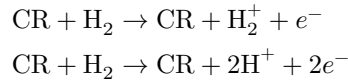
This paper is organized as follows: Section 2 introduces a bioenergetic mechanism driven by CR ionization of hydrogen and argues that this may also repre-

sent the origin of chemiosmosis. Possible experimental tests and further discussions are summarized in the final section.

2 Cosmic Ray Ionization of Hydrogen Molecules

Cosmic rays are high-energy particles that travel through the galaxy at nearly the speed of light, first discovered by Victor Hess in 1912. The origin of CRs in the Milky Way is generally attributed to supernova explosions, though the source of ultra-high-energy CRs remains mysterious. The CR energy spectrum follows roughly a power law with different spectral indices across various energy ranges. Precise measurements of this spectrum help us understand CR source properties and their propagation through the universe. Numerous experiments have measured CRs, including the Alpha Magnetic Spectrometer [?], Fermi Large Area Telescope [?], Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics [?], Dark Matter Particle Explorer [?], and Calorimetric Electron Telescope [?].

Cosmic rays interact with the interstellar medium in many ways, but CR ionization of hydrogen represents the dominant interaction for low-energy cosmic rays in molecular clouds. This process primarily involves the following reactions:



where CR denotes charged CR particles and secondary particles produced by collisions between CRs and the molecular cloud, such as protons, heavy nuclei, electrons, positrons, etc. If the produced electrons have sufficient energy, they can induce further ionizations of hydrogen molecules due to their relatively short range.

It should be noted that the formation of H_2^+ (the process in Eq. (1)) is the major pathway. The production rate of electrons per H_2 can be described as [?]:

$$\zeta_e = \int_{I(\text{H}_2)}^{E_{\max}} \sum_k j_k(E_k) [1 + \phi_k(E_k)] \sigma_{\text{ion},k}(E_k) dE_k,$$

where $j_k(E_k)$ is the number of CR particles per unit area, time, solid angle, and energy for CR component k ; $I(\text{H}_2)$ is the ionization potential of the hydrogen molecule; E_{\max} is the maximum energy considered; and σ_{ion} is the cross section for ionization of molecular hydrogen. The quantity $\phi_k(E_k)$ is a correction factor accounting for ionization of hydrogen molecules by secondary electrons, described as [?]:

$$\phi_k(E_k) \equiv \int_{I(\text{H}_2)}^{E_{\max}^e} P(E_k, E'_e) \sigma_{\text{ion},e}(E'_e) dE'_e,$$

where $P(E_k, E'_e)$ is the probability that a secondary electron with energy E'_e is ejected from ionization by CR particles with energy E_k , and E_{\max}^e is the maximum energy of secondary electrons. More detailed calculations can be found in Ref. [?].

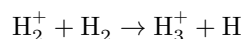
High-energy photons such as X-rays and gamma rays can also knock electrons out of hydrogen molecules through the photoelectric effect, though these processes are not discussed in this work.

3 Cosmic Ray-driven Bioenergetics and the Origin of Chemiosmosis

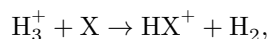
Molecular clouds are a type of interstellar cloud with average densities of about 10^2 - 10^4 molecules per cubic centimeter, predominantly molecular hydrogen. The typical temperature of a molecular cloud is about 10-20 Kelvin. Although hydrogen's melting and boiling points are 13.99 K and 20.27 K respectively, hydrogen remains in the gaseous phase due to low pressure. We suppose that molecular cloud life possesses a cell-like membrane structure. If hydrogen could be enriched within such a cell, the internal hydrogen pressure would increase and hydrogen might maintain a liquid state. In this scenario, the internal environment of molecular cloud life would be liquid hydrogen, similar to the liquid water environment of cells on Earth, which would be highly favorable for biochemical reactions.

Cosmic rays represent a vital energy source that contributes to both the ionization and heating of molecular clouds and constitute a critical component in the chemistry and dynamics of the interstellar medium [?]. The essence of bioenergetics is to gradually release energy carried by electrons through the electron transport chain to sustain life activities. The CR ionization process can produce many electrons with suitable energy levels. We therefore propose that CR-induced ionization of hydrogen powers the electron transport chain of lifeforms in molecular clouds. While electrons may first interact with other molecules such as nicotinamide adenine dinucleotide (NAD^+), it is more natural based on principles of simplicity and optimal energy utilization for electrons produced by CR ionization to enter the electron transport chain directly. The electron donor remains molecular hydrogen, and the energy essentially derives from the CR ionization process, with or without an intermediate electron transporter. Furthermore, Ref. [?] found that the flux of either CR electrons or protons increases at low energies, producing many more suitable electrons for the electron transport chain.

The H_2^+ ions produced from CR ionization of hydrogen molecules can be rapidly depleted by reacting with molecular hydrogen as follows [?]:



Then H_3^+ is removed by reacting with neutral molecules through proton transfer reactions:



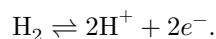
where X is a neutral molecule in the nebula, such as CO, H_2O , N_2 , etc. The products of reactions between H_2^+ ions and carbon compounds may be crucial for synthesizing organic molecules in molecular cloud lifeforms. Hydrogen atoms are further ionized to H^+ or form hydrogen molecules through grain-catalyzed reactions until the electron's energy is suitable for entering the electron transport chain and pumping protons into the intermembrane space.

Like lifeforms on Earth, the electrochemical proton gradient drives ATP synthesis. The electron flow then combines with H^+ to form hydrogen atoms acting as donors and acceptors. Other acceptors may exist but are not discussed in detail here. A schematic representation of this process is shown in Fig. 1 [Figure 1: see original paper]. In general, the cellular fluid of molecular cloud life is a mixture of hydrogen molecules, hydrogen atoms, and protons.

Although some energetic secondary electrons may not directly participate in the electron transport chain, further ionization of H_2 and hydrogen atoms by secondary electrons reduces electron energy while simultaneously increasing the number of electrons and protons. This process maximizes the utilization efficiency of high-energy CRs as part of their energy is transformed and modified. The exact extent of this impact depends on the density of lifeforms and energy utilization efficiency, which we plan to investigate in future work. In addition, many other factors (e.g., propagation parameters, primary cosmic ray flux, and the density and distribution of molecular clouds) can influence the cosmic ray energy spectrum. It would be technically challenging to distinguish the influence of lifeforms from so many complicated factors.

4 Discussion

The CR-driven bioenergetics discussed in this paper is essentially a reversible redox reaction:



This process is similar to bacteria that use hydrogen as an energy source, catalyzed by hydrogenases. The ability to metabolize hydrogen is widespread and appears inherent to Earth's life; more than 30% of known microbial taxa possess hydrogenase genes [?]. Furthermore, approximately 70% of gastrointestinal microbial species listed in the Human Microbiome Project contain the genetic

information necessary for metabolizing hydrogen molecules [?]. If Earth's atmosphere was initially rich in hydrogen, hydrogenases likely evolved naturally to utilize molecular hydrogen as an energy source. Hydrogen molecules have been identified as electron donors in hydrothermal vent animal symbioses [?].

We propose that the Last Universal Common Ancestor (LUCA) originated from the pre-solar nebula as suggested by the Nebula-Relay hypothesis and was driven by cosmic ray ionization of hydrogen molecules. LUCA would therefore be related to hydrogen bacteria and utilize molecular hydrogen as an electron donor. Ref. [?] found that LUCA may have been a heat-loving microbe feeding on hydrogen gas, based on surveying nearly two thousand genomes of modern microbes. Ref. [?] similarly argued that LUCA's first electron donor was hydrogen, consistent with our model. However, these studies propose carbon dioxide as the electron acceptor, which differs from the mechanism discussed here.

Testing this bioenergetic mechanism is challenging, but one possible approach involves simulating the bioenergetic process of molecular cloud life by placing microorganisms closest to LUCA in liquid hydrogen, irradiating them with high-energy particles, and studying their biochemical processes.

5 Summary

This paper discusses the bioenergetics of life in molecular clouds and introduces a new bioenergetic mechanism driven by CR ionization of hydrogen. In this model, harmful CR radiation is transformed into bioavailable energy. The main prediction is that LUCA was a type of microbe that used hydrogen molecules as donors for electron transport chains. Protons generated from CR ionization and subsequent chemical reactions can be used for transmembrane transport and ATP formation, potentially explaining the origin of chemiosmosis. Life in molecular clouds could thereby obtain sufficient energy to sustain its activities.

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