

Life as a Phase State of Matter

A Nanodust Scenario for the Origin of Living Systems

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Abstract

The origin of life is commonly treated as a biochemical anomaly or as the result of a rare coincidence of favorable conditions. In this work, a fundamentally different framework is proposed, in which **life is defined as a stable nonequilibrium phase state of matter**. Within this approach, the emergence of life is understood not as a singular chemical event, but as a **phase transition** driven by extreme entropy production and subsequent negentropic self-organization.

It is argued that the decisive physical environment for this transition is the **nanodust phase** formed at the interface between planetary matter and interplanetary space under conditions of mega-impacts, intense meteoritic bombardment, and accompanying **cosmic ionizing radiation**. These processes lead to catastrophic fragmentation of macroscopic crystalline structures, plasma formation, aerosol condensation, and continuous traversal of matter across a broad spectrum of phase states.

A central role is assigned to **proton invasion**, which acts as a global entropic factor producing persistent deviation from equilibrium. Life is interpreted as a **stabilizing response of matter to proton overload**, realized through partial proton assimilation, sustained energy dissipation, and the formation of stable nonequilibrium regimes. Both first-order and second-order phase transitions are essential: the former provide repeated structural restructuring, while the latter enable symmetry breaking, collective behavior, chirality, and self-organization.

In contrast to local terrestrial scenarios restricted to narrow physical conditions, the nanodust scenario spans an exceptionally wide phase-space—from plasma to solid and liquid-crystalline phases, and from temperatures of millions of degrees to cryogenic conditions. This breadth makes the phase transition toward living matter statistically expected rather than exceptional.

Keywords

origin of life; phase state of matter; nanodust; nonequilibrium systems; entropy and negentropy; energy dissipation; proton invasion; phase transitions; self-organization; cosmic ionizing radiation; protometabolism; interplanetary environment

Introduction

The problem of the origin of life is traditionally addressed within separate disciplines—chemistry, biology, geology, or astrophysics. This fragmented approach has produced numerous scenarios, including hydrothermal vents, the RNA world, panspermia, and various pathways of abiotic organic synthesis. However, none of these models answers the fundamental question: **why nonliving matter should have transitioned into a living state at all.**

In this work, an alternative **phase-based approach** is proposed. The central thesis is that life is neither a unique chemical accident nor the result of an improbable coincidence of conditions. Instead, **life is a stable nonequilibrium phase state of matter**, emerging as a response to extreme entropic disturbances in planetary and interplanetary environments.

A decisive role in this process is played by **proton invasion and nanodust**—a state of matter formed through catastrophic destruction of macroscopic crystalline structures during mega-impacts, intense meteoritic bombardment, and associated **cosmic ionizing radiation**. It is within the nanodust phase that maximal energy dissipation, continuous phase transitions, and negentropic processes arise, creating the physical conditions necessary for the emergence of living matter.

1. Life as a Phase State of Matter

In classical biology, life is defined through a set of functional attributes: metabolism, replication, heredity, and adaptation. Such definitions describe manifestations of life but do not explain its physical nature.

Within the proposed framework, life is considered a **phase state of matter**, analogous to other nonequilibrium phases such as convection, turbulence, and liquid-crystalline ordering. Like these systems, life:

- exists only under continuous energy flux,
- does not approach thermodynamic equilibrium,
- maintains its structure through dissipation.

Thus, life is not a substance or an object, but a **mode of matter organization** stable within a specific range of environmental parameters. A key consequence of this view is that the origin of life should be understood as a **phase transition**, rather than as a singular event or a “miracle.”

2. Entropic Explosion and the Birth of Nanodust

The formation of early Earth was accompanied by intense mega-impacts and heavy meteoritic bombardment. These processes led to:

- destruction of macroscopic silicate crystals,
- evaporation and plasma formation,
- rapid condensation into aerosols and nanoparticles.

The transformation of ordered macroscopic crystals into nanodust corresponds to a sharp increase in entropy. The transition from a single crystal to an ensemble of nanoparticles dramatically increases the number of degrees of freedom, surface energy, and chemical reactivity.

According to the Brown–Le Chatelier principle, physical and chemical systems driven far from equilibrium inevitably respond by generating compensatory stabilizing processes. In this case, the entropic explosion creates a substantial **negentropic potential**, which is realized through the emergence of new stable regimes.

Nanodust is therefore not merely finely dispersed matter, but a **distinct phase form** in which surface effects dominate, defects and active centers become ubiquitous, and phase transitions occur continuously.

3. Nanodust as a Stage of Phase Transitions

In a nanodust environment, matter resides predominantly at phase boundaries:

- between gas and condensate,
- between amorphous and partially crystalline states,
- between solid, liquid, and liquid-crystalline regimes.

In this work, phase transitions are considered in a broad physical sense and include both **first-order transitions** (melting, condensation, crystallization) and **second-order transitions**, associated with symmetry breaking, the emergence of long-range correlations, and collective modes.

Second-order phase transitions play a key role in self-organization processes, the formation of liquid-crystalline states, the emergence of chirality, and the stabilization of nonequilibrium phase regimes. The origin of life should therefore be viewed as the result of the combined action of phase transitions of different types across an exceptionally wide range of conditions.

Phase boundaries are regions of maximal energy dissipation, high component mobility, reduced barriers to self-organization, and the emergence of structural memory. Liquid-crystalline states

are of particular importance, as they combine order with mobility and support collective dynamics.

From the outset, life forms not within stable phases, but as a **persistent regime at their boundaries**. This reveals a deep connection between biological organization and the physics of phase transitions.

4. Ionizing Radiation and Proton Invasion

Catastrophic events in Earth's early history were accompanied by intense ionizing radiation. A central role was played by cosmic protons, which:

- drastically altered electric charge distributions,
- shifted pH and redox potentials,
- induced ionization, radical formation, and atomic transmutations.

The penetration of protons into the primary nanodust environment led to a condition that can be described as **proton invasion**, representing a chronic deviation from equilibrium.

In this context, life did not arise as a goal-driven or programmed process. Rather, it emerged as a **forced stabilizing response of nonliving matter** to excessive proton activity. Hydrogenation, hydration, restructuring of mineral networks, synthesis of water, and formation of organic structures are interpreted not as directed acts, but as mechanisms for reducing proton overload.

In this sense, protons act as a physical “pathogen,” while life represents a **mode of proton assimilation**.

5. Proton Assimilation as a Universal Process

Crucially, proton assimilation is not limited to carbon chemistry. It affects:

- mineral lattices,
- silicate and oxide structures,
- nanocrystals and amorphous phases.

Organic molecules constitute only one realization of a more general stabilization process acting under proton overload. Consequently, early life cannot be regarded as a purely carbon-centered system. It emerges as a **hybrid phase**, integrating organic and inorganic components united by a common function: proton assimilation and maintenance of a nonequilibrium state.

Complete proton binding would drive the system toward a new static equilibrium, effectively terminating phase dynamics. Partial assimilation, by contrast:

- preserves reactivity,
- maintains energy gradients,
- ensures process directionality.

Negentropy is thus realized not through maximal order, but through **controlled instability**.

6. Unsaturated Bonds as Phase Boundaries

Unsaturated and conjugated chemical structures occupy an intermediate position between different phase states. They are neither inert gas-phase molecules nor rigid crystalline forms. This makes them functional analogues of phase boundaries, where:

- energy dissipation is maximal,
- structural rearrangement is enhanced,
- self-organization is favored.

For this reason, polymerization, templating, and formation of complex molecular ensembles are most efficient in systems rich in unsaturated and conjugated bonds. This is not a contingent chemical preference, but a direct consequence of phase dynamics.

7. Protometabolism and Phase Selection

Under sustained energy and proton flux, chemical processes naturally shift from linear reactions to cyclic regimes. These cycles retain energy, redistribute matter, and reduce sensitivity to fluctuations, marking the emergence of **protometabolism**—not as biochemistry, but as a phase regime.

Protometabolic structures form ensembles that compete for energy and proton flux. Selection acts not on molecules, but on **modes of dissipation and stabilization**. This process is analogous in logic to Wallace–Darwinian selection, though it precedes biological evolution and operates on physical regimes rather than organisms.

8. Structural Memory and Pre-Information

Repeated realization of stable regimes leads to the emergence of **structural memory**—the ability of a system to restore its mode of organization after perturbation. This constitutes a form of **pre-information**, preceding genetic codes and symbolic storage.

At this stage, reproducibility applies to regimes of operation, not to molecular sequences. Nevertheless, it establishes the physical foundation for subsequent biological inheritance.

9. Phase-Space Range and the Probability of Life

In contrast to local terrestrial scenarios limited to narrow ranges of parameters, the nanodust scenario spans an exceptionally broad **range of phase states and energy regimes**:

- from plasma to solid and liquid-crystalline phases,
- from temperatures of millions of degrees to cryogenic conditions.

An exceptionally wide range of phase states—from plasma and high-energy regimes to solid and liquid-crystalline phases—implies repeated traversal of matter through both first-order phase transitions and critical second-order transitions. This combination *обеспечивает* maximal energy dissipation, the growth of negentropic potential, and the formation of stable regimes capable of undergoing a phase transition toward living matter.

Repeated traversal of this extreme phase-space maximizes dissipation and negentropic potential. As a result, the transition to living matter becomes **statistically favored rather than exceptional**.

Life arises not in a specific place, but within a **specific range of phase states of matter**.

Epilogue: From Phase Regime to Biological Specificity

This work deliberately restricts itself to the phase and physicochemical prerequisites of life's origin. Genetic codes, membranes, and enzymes are not introduced in their biological sense.

However, the results naturally lead to the next level of organization. Subsequent work will show that:

- nanocrystals and nanodisperse silicates localize and amplify negentropic regimes,
- silanes and functionalized surfaces act as primary molecular imprints,
- polyaromatic structures bridge protometabolism and information processes,
- molecular chimeras create prerequisites for the emergence of the genetic code.

Biological specificity is thus interpreted not as a starting point, but as a **late phase of a more general physical process.**

Final Statement

Life is a phase state of matter that arises with the highest probability in zones of maximal contrast between planetary matter and interplanetary space.

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