Could Icy Interstellar Dust Form the Largest Primordial Soup in the Universe?

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Abstract

In the RNA World hypothesis, it is generally assumed that self-replicating RNA emerged from a primordial soup of amino acids approximately 500 million years before the advent of life on Earth. Recently, prebiotic molecules such as glycolaldehyde and amino acetonitrile have been discovered in abundance in nebulae like Sagittarius B2. This paper proposes that icy grains within these nebulae could act as primordial soups and explores the implications of this hypothesis. It is argued that the sheer abundance of these grains in a typical nebula makes their collective volume astronomically greater than Earths primitive oceans, thus favouring the likelihood of an RNA self-replicator emerging within this environment based on volume arguments. The likelihood of naturally producing the first self-replicator may be significantly lower than previously envisioned, necessitating the contribution of a larger primordial soup spread across a nebula and functioning for billions of years before the emergence of life on Earth. According to this model, Earth could have been seeded by panspermia following the emergence of a self-replicator on nearby icy interstellar dust. Finally, we discuss the Fermi paradox in the context of this model.

1 Introduction

The spectroscopy of meteorites has revealed the presence of indigenous amino acids[1]. More than 70 amino acids have been found in the Murchison meteorite alone[2]. Sagittarius B2, a nebula located 390 light years from the center of the Milky Way, exhibits the richest organic composition observed to date in a nebula; to date, the presence of at least 70 organic compounds has been reported[3]. More recently, glycolaldehyde CH_2OHCHO, the first reported interstellar sugar, and amino acetonitrile NH_2CH_2CN, a direct precursor of the simplest amino acid, glycine, were also detected in this nebula[4, 5].

The concentration of gas within a typical nebula is thought to be too low to account for the rich organic chemistry observed. An icy grain model is instead proposed. A typical interstellar icy grain has a size ranging from 0.01m^3 to 0.1m^3 and is estimated to constitute 0.5 to 1% of the hydrogenous mass of the nebula[6]. Infrared measurements from space telescopes have confirmed that these grains are enveloped in frozen materials, with H_2O being the most abundant[7]. According to the grain chemistry model, icy grains accumulate ambient organics on their surfaces. Cosmic ray ionization, surface diffusion effects, and ambient temperature changes cause the simple organics to react and then outgas, creating the rich products observed in space[8]. The icy grain model is further supported by laboratory experiments simulating outer space conditions, which have reproduced part of the organic richness observed in nebulae[9, 10]. These experiments also produced amino acids such as serine, glycine, and alanine in one instance[11], and over 16 amino acids in another[12]. In the Bernstein experiment, the carbon yield of glycine was 0.5%, compared to a yield of 1.2 to 4.7% in revised Miller-Urey type experiments[13].

Organic matter is found almost everywhere in space, including diffuse clouds, planetary nebulae, star-forming regions, comets, asteroids, and meteorites[14]. Space probes from NASA's Stardust mission returned to Earth with a measurable deposition of indigenous organics[15]. An emerging view suggests that comets may have sprinkled organic space dust on primitive Earth, potentially helping to kickstart life[16].

Meanwhile, on Earth, the search for a self-replicating molecule continues to puzzle researchers in laboratories. The question of how amino acids and organic polymers first assembled into a structure capable of undergoing natural selection remains the great unanswered challenge of abiogenesis. Ribozyme-like structures, which have the ability to both encode information and catalyze reactions two core requirements of life may offer the most promising avenue for investigation[17]. In the RNA world hypothesis, primitive Earth served as an incubator for organic materials in what is known as the primordial soup, a milieu where organic compounds chemically interacted to form increasingly complex structures.

2 The Origins of the First Self-Replicator

Once self-replication originates in an RNA molecule, it becomes subject to the laws of natural selection, which can drive its evolution into more complex systems. However, the challenge lies in generating this first self-replicator. In a primordial soup, simple organic molecules interact, forming products with varying complexities. According to the RNA world hypothesis, the first self-replicator is thought to emerge randomly through an iterative process involving various atomic rearrangements of organic matter. This process, in which different arrangements are tested until a self-replicator is found, resembles a brute-force search algorithm. The primordial soup functions as an iteration engine, traversing the set of possible atomic arrangements in search of a self-replicator. Considering that every drop of ocean water contains approximately 1.5 x 10^{21} molecules, this search is conducted on a massively parallel scale.

For the search to be considered brute force, certain assumptions are made:

1. Any single collision between sufficiently complex organic molecules can yield new organic products with varying probabilities, and each collision serves as one iteration.
2. Each iteration has a non-zero chance of producing a self-replicator.
3. The search does not benefit from prior failed iterations to reduce the search space or adjust its strategy, meaning the search has no memory.
4. Any region of space where iteration occurs over time will be considered a primordial soup, with its iterative contribution (I_c) proportional to a) the mass (m) of iterating organic material within the soup, b) the total time (t) the soup is iterating, and c) the efficiency (k) of the process:

$$I_c \propto k \cdot m \cdot t \tag{1}$$

Some factors could potentially reduce the difficulty of the search. For example, the formation of stable environments with complex organic compounds could lead to progressively more complex layers of these compounds. This development would allow future iterations to indirectly benefit from prior search efforts. Such a scenario could facilitate the search. However, despite this potential facilitation, the search space could still be so vast that our primary thesis of brute-force remains approximative in practice.

Many environments of varying nature, composition, or ambient temperature could iterate over the problem of creating a self-replicator. We can attribute the odds of producing of the first self-replicator to the largest such environment we can identify. Given that nebulae are producing complex organic chemistry and that amino acids are likely present on icy grains, it opens up the possibility that they contribute to the search for a self-replicator. In this paper, it is proposed that nebulae, with their environment rich in organic compounds, allow icy grains to form a primordial soup on their surfaces, making the scale of this environment larger than any other.

3 Example Application of the Model

In nebulae such as Sagittarius B2, icy grains travel through a thin gas averaging 3000 particles/cm^3. Over extended periods, ambient organic molecules accumulate on the surface of these grains. This accumulation creates a microenvironment where organics interact through diffusion and other physical processes, leading to the formation of chemical products with various complexities. Furthermore, if we assume that each individual reaction product has a non-zero chance of producing a self-replicator, then each grain essentially acts as a minuscule primordial soup.

If and when a self-replicator is created, it will undergo asexual reproduction, becoming subject to natural selection. According to the theory of evolution, the self-replicator will either evolve to adapt to its current environment or, if it fails to adapt, will go extinct and its components will serve as reagents for future reactions. If it successfully adapts, it will produce numerous copies of itself by consuming the available organic matter on the icy grain. Such a grain, which facilitates this process, will be referred to as a producer. The production of self-replicators will continue until a limiting factor is encountered, such as exhausting the supply of organic matter on the grain.

A producer, during its journey through space, may traverse various climate zones, primarily delineated by its proximity to a star. These zones are generally defined by factors such as temperature, ambient radiation, bath composition, types of organic matter, concentration levels, and so forth. The habitable zone for a producer could be quite extensive. Solar wind currents, turbulence, or collisions might transport producers across vast distances. Regions within nebulae that have higher temperatures are typically found in areas with intense star and planetary formations. Since the rate of chemical reactions increases with temperature, a producer is likely to be more efficient in such regions.

During this process, over aeons, stars and planets may form within the habitable zone. As planets accrete, they reach temperatures exceeding the melting point of metals, leading to the vaporization of most complex organic matter. It's likely that self-replicators might not survive the intense conditions of planetary accretion. However, comets orbiting star systems can accumulate icy grains as they travel through space. These comets may then outgas their contents, including potentially self-replicating molecules, onto nearby planets as they journey inward towards the star.

Finally, a producer could reach a planet directly or by attaching to a comet and then outgassing onto the planet. In this scenario, it would act as the source of self-replicating structures to the planet's possibly pre-existing but inactive bath of organic matter. The structure would replicate by consuming the primordial organic soup as food, evolving into a more complex stage. Multiple planets in the vicinity of the comet or the producer could be sprinkled with copies of the self-replicator, potentially creating a cluster of primitive life forms in a stellar region.

If icy grains indeed act as primordial soups, then any reasonable estimation of their contribution to the search for a randomly produced self-replicator suggests an overwhelming probability that a self-replicator first formed within this environment, compared to other identifiable primordial soup environments. This is because the iterative process on icy grains significantly outperforms that of other identifiable primordial soups. For instance, an 8 billion-year-old nebula with a mass of 10^6 solar masses, where 1% of its mass consists of icy grains (which are typical values), would offer a contribution to the formation of self-replicators that dwarfs by orders of magnitude the contribution from Earths primitive oceans during its 500-million-year primordial soup epoch.

4 Discussion and the Fermi Paradox

Life on Earth is often thought to have evolved from inorganic matter over a span of 4 billion years. The initial 500 million years of this process, known as the abiogenesis phase, is believed to have occurred in Earth's primordial soup. If this is true, the process would be self-contained to the planet, somewhat independent of the surrounding interstellar organic environment and its availability, and could feasibly be replicated on any other Earth-like planet within a similar timeframe. However, this assumption raises two unanswered questions:

1. Why did life emerge 10 billion years after the Big Bang and not as soon as the first batch of potentially Earth-like planets formed around 7 billion years ago?

2. If life did evolve earlier on other planets, why is there an apparent lack of evidence for intelligent extraterrestrial civilizations a question encapsulated in the Fermi paradox.

If intelligent life is indeed rare and assuming it does not always destroy itself, a plausible explanation could be that it requires most of the time since the Big Bang to evolve, along with a substantial amount of space. Consistent with these constraints, a necessary preliminary step before life could evolve on an Earth-like planet was presented. The challenge of finding the first self-replicator might be significantly greater than originally assumed. This suggests that an ocean-sized primordial soup would have limited chances of iterating over a self-replicator within the identified timeframe of 500 million years. Many Earth-like planets could be in a state of primordial soup, essentially in limbo awaiting for the creation of a self-replicator. The difficulty of a brute-force iterative search for the first self-replicator could be such that only a nebula-wide process, iterating for 8 to 10 billion years, would have a reasonable chance of producing one. In this scenario, Earth would have formed in a part of the galaxy where a self-replicator had already been created in space. This leads to the expectation, in line with the Fermi paradox, that we might be alone and perhaps even the first. This scenario suggests a universe rich in organic material, as observed, but with intelligent life being exceedingly rare, as hinted at by present observations. It presents a model for the origins of life that is consistent with current observations and offers a resolution to the Fermi paradox in the context of the abundance of organic matter in space.

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