Preprint release. March 18, 2015 (Revision September 14, 2020)

Does interstellar dust form the largest primordial soup in the universe?

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Abstract: In the abiogenesis hypothesis, self-replicating RNA is generally assumed to have arisen out of a primordial soup of amino acids no later than 500 million years before life on Earth. Recently, prebiotic molecules such as glycolaldehyde and amino acetonitrile were found to be abundant in nebulas such as Sagittarius B2. In this paper I propose that icy grains within nebulas can act as tiny primordial soups, and I investigate the consequences of such. I further argue that a typical nebula would be astronomically more likely to create a self-replicator than the combined iterative power available in Earth's primitive oceans. Finding the first self-replicator could be a problem significantly more difficult than previously envisioned, requiring the contribution of a larger primordial soup spread across a nebula and operating for billions of years prior to life on Earth. Finally, we discuss the Fermi paradox in the context of a mechanism by which life could be expected to lag the Big Bang by 10 billion years, hence suggesting that we may not only be alone, but also not inconceivably the first.

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 390 light years away from the centre of the Milky Way, exhibits the richest organic composition observed to date in a nebula. In fact, over 70 organic compounds have been reported to be present in it[3] and the numbers are growing. More recently, glycolaldehyde CH_2OHCHO, the first 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 explain the rich organic chemistry. An icy grain model is instead suggested. A typical interstellar icy grain has a size of $0.01\mu m^3$ to $0.1\mu m^3$ and would equal 0.5 to 1% of the hydrogenous mass of the nebula[6]. Infrared measurements from space telescopes confirmed that frozen materials envelope the grain, of which H_2O is 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 will cause the simple organics to react, creating the rich products observed in space[8]. The icy grain model is further supported by laboratory experiments analogous to outer space conditions, which reproduced part of the observed organic richness of nebulas[9, 10], as well as produced the amino acids serine, glycine and alanine in one experiment[11] and over 16 amino acids in another[12]. In the Bernstein experiment, the carbon yield of glycine was 0.5% in comparison to a yield of 1.2 to 4.7% for revised Miller-Urey type experiments[13].

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

Meanwhile on Earth, the search for a self-replicating molecule continues in laboratories. How amino acids and organic polymers first assembled into a structure undergoing natural selection remains the great unanswered question of abiogenesis. Ribozyme-like structures, able to both encode information and catalyze reactions - two core requirements of life, may provide the best investigative path[17]. Primitive Earth served as an incubator for organic materials in what is called the primordial soup, where organic compounds were chemically interacting to form progressively more complex structures.

The origins of the first self-replicator

Once a self-replicating molecule originates, it undergoes natural selection and can quickly evolve into complex systems. But how hard is it to generate the first self-replicator? In a primordial soup, simple organic molecules interact to form products of random complexities. Under the worst-case scenario, the first self-replicator can be produced by an iterative process over the set of all possible atomic arrangements of organic matter. As each arrangement has to be tried until a self-replicator is found, finding it would be a problem akin to the traveling salesman problem. The primordial soup acts as an iteration engine that traverses the set of possible atomic arrangements in search of a self-replicator. Since every drop of water in the ocean contains approximately 1.5×10^{21} molecules, the search is massively parallel. Creating life can be seen as a brute force search problem.

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

1) Any single collision between sufficiently complex organic molecules yields products with varying probabilities and 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 to adjust its search strategy.
4) Any region of space where iteration takes place over time will be considered a primordial soup whose iterative contribution (I_c) is 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:

$$(1) \qquad I_c \propto k \cdot m \cdot t$$

Some factors could simplify the problem, but we assume that they do not reduce the search space enough to change the thesis of this model. For instance, many arrangements of organic matter could lead to a working self-replicator. This would reduce the number of iterations required for a solution as it only needs to find one out of all possible self-replicators. Additionally, complex but stable molecular arrangements could be created during the process, resulting in new intermediate stable layers. The primordial soup is currently believed to be the highest layer before the self-replicator, but are there any layers in-between? If so, each intermediate stable layer would be a milestone along the path of increased complexity, allowing future iterations to benefit from prior search efforts. Any of these could be true, and each would facilitate the search, but nonetheless the search space could still be astronomical such that our primary thesis holds.

From these assumptions, many environments of different nature, composition or ambient temperature could iterate over the problem. Since nebulas are producing a complex organic chemistry and that amino acids are likely on icy grains, this opens the possibility that they are contributing to the search for a self-replicator. Here I propose that in nebulas, with an environment rich in organic compounds, icy grains form a primordial soup on their surfaces.

Example application of the model

In nebulas such a Sagittarius B2 icy grains travel through a thin gas of 3000 particles/cm^3. Over time, ambient organic molecules will accumulate over the surface of the grain. A micro-environment will exist where organics interact through diffusion and other physical processes to create chemical products of various complexities. Furthermore, if we assume that the product of each individual reaction has a non-zero chance that it will produce a self-replicator, then the grain acts as a minuscule primordial soup.

If and when a self-replicator is created, asexual reproduction will subject it to natural selection. The self-replicator will quickly evolve to adapt its physiology for its current environment or, if it fails to adapt, it will go extinct and will serve as reagents for a future reaction. If it does adapt, numerous copies of it will be produced by consuming the remaining organic matter on the icy grain. Such a grain will hereafter be called a *producer*. The production will continue until the grain runs out of food or out of space.

A producer, during its journey into space, may traverse different climate-zones delimited mostly by its proximity to a star, and generally defined by temperature, ambient radiation, bath composition, organic matter type, concentration levels, etc. The habitable zone of a producer may be very large. Wind currents, turbulence or collisions could carry producers across large distances. Regions of higher temperatures in nebulas are found in areas of intense star and planetary formations. As the rate of chemical reactions increases with temperature, a producer is likely more efficient in such a region.

During this process, stars and planets may form within the habitable zone over aeons. As planets accrete, they reach temperatures above the melting point of metals, vaporizing most of the complex organic matter. Self-replicators might not survive the planetary accretion process, but comets orbiting star systems will accumulate icy-grains as they travel through space. The comets will then outgas their contents on nearby planets as they travel inwards.

Finally, a producer could land on planet directly, or by latching on comet then outgassing onto a planet. In this case it acts as the source of the self-replicating structure to a planet's possible pre-existing but inactive bath of organic matter. The structure would have replicated by consuming the primordial organic soup as food and would have evolved into a more complex stage of evolution. Multiple planets in the vicinity of the comet or the producer could be sprinkled with copies of the self-replicator, creating a cluster of (primitive) life in a stellar region.

To understand the purpose of icy grains in the creation of life, it helps to treat them as computational engines solving a massively parallel algorithmic problem. The icy grains have the role of a computing node. Agglomerations of nodes that provide the largest share of computing power have the highest chances of finding the first self-replicator.

Almost any reasonable estimation of the contribution of icy grains to the search for a randomly produced self-replicator assign a probability nearing unity to that of a self-replicator randomly occurring on an icy grain, because this iterative solution outclasses anything else that's available on the market. For instance, an 8 billion years old nebula of 10^6 solar masses, where 1% of its mass is in the form of icy grains, would have an iteration rate that completely dwarfs (by dozens of order of magnitudes higher) that which was available in Earth's primitive oceans during its 500 minion year primordial soup epoch.

Discussion and the Fermi paradox

Life on Earth is often thought to have evolved from inorganic matter over the course of 4 billion years. The initial 500 million years of the process is the abiogenesis phase and is believed to have occurred in the primordial soup of Earth. If true, the process would be self contained to the planet, be somewhat independent of the surrounding interstellar organic environment and availability and could easily be repeated on any other Earth-like planet within a comparable time frame. This assumption leaves two unanswered questions. 1) Why did it occur 10 billion years after the Big Bang and not as soon as the first batch of planets was formed 7 billion years ago - some of them surely Earth-like? 2) If life did evolve sooner on other planets, why is there a lack of evidence for intelligent extraterrestrial civilizations - a.k.a. the Fermi paradox.

If intelligent life is indeed rare, and does not necessarily destroy itself, a possible expectation would be that it takes most of the available time since the Big Bang to evolve, and a sizeable amount of space to do so. In this paper I presented a preliminary step that would be required before life could evolve on an Earth-like planet. The problem of finding the first self-replicator could be significantly more difficult than originally assumed, such that an ocean-sized primordial soup would have no reasonable chances to iterate over a self-replicator within the identified time-frame of 500 million years. There may be thousands of Earth-like planets stuck in a state of primordial soup waiting for a self-replicator to be created, and the brute force search difficulty could be such that only a nebula-wide process, iterating for 8 to 10 billion years, would have a reasonable chance to produce one. In this scenario, Earth would have formed in an area of the galaxy after a self-replicator was created in space, and would set the expectation of the Fermi paradox to be that we are possibly alone and perhaps even the first. In this scenario, we would expect a universe rich in organic material -as observed-, yet life to be exceedingly rare. Finally, a falsifiable prediction of the model would be that if any life were to be found elsewhere in the solar system or in its vicinity, such life would share common descent to an original self-replicator and would thus be part of the same tree of life as us.

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