Gaia Theory and The Gaia Bottleneck Hypothesis

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1 Introduction

The prerequisites for life seem to be abundantly available in our Universe. However, the Universe is not teeming with diverse life like on our planet. The most common route to explain this observation is the extremely low probability of emergence of life itself (an emergence bottleneck). In this report we look at an alternative hypothesis based on the framework of the Gaia theory that tries to explain our observations.

Gaia hypothesis is a very fascinating perspective of looking at how life on a planet interacts with its home and affects the planet itself. We will be looking at a hypothesis based on the framework of the Gaia theory which is a possible answer to the Fermi paradox - an answer to "Where is Everyone?". Furthermore it stresses on how existence and sustenance of life is not just a result of certain "habitable" conditions being present on a planet but rather argues that a planet's habitability is sustained due to presence of life. In simpler words a planet needs to be **inhabited to remain habitable** in the long run.

The modern version of Gaia theory is studied under the field of Earth System science. "Earth System science embraces chemistry, physics, biology, mathematics and applied sciences in transcending disciplinary boundaries to treat the Earth as an integrated system. It seeks a deeper understanding of the physical, chemical, biological and human interactions that determine the past, current and future states of the Earth"

2 What is Gaia?

I'd like to begin with a quote which sums up why a thought process like that of the Gaia hypothesis is natural.

"It is at least not impossible to regard the earth's parts—soil, mountains, rivers, atmosphere etc,—as organs or parts of organs of a coordinated whole, each part with its definite function. And if we could see this whole, as a whole, through a great period of time, we might perceive not only organs with coordinated functions, but possibly also that process of consumption as replacement which in biology we call metabolism, or growth. In such case we would have all the visible attributes of a living thing, which we do not realize to be such because it is too big, and its life processes too slow."

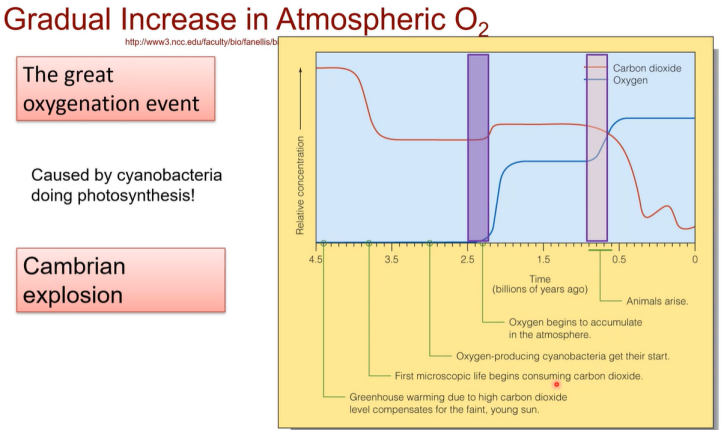
— Quoted by Stephan Harding in Animate Earth.

The Gaia theory has evolved a lot since it was developed by the chemist James Lovelock and co-developed by the microbiologist Lynn Margulis in the 1970s. Originally, Gaia hypothesis proposed that all organisms and their inorganic surroundings on Earth are closely integrated to form a single and self-regulating complex system, maintaining the conditions for life on the planet. This was later modified to it's more inclusive and accepted form: "The **Earth System** behaves as a single, self-regulating system with physical, chemical, biological, and human components."

There are a ton of phenomena that naturally lead to a thought process similar to that of Gaia theory. Here are some observations which hint at there being a stable, self-regulating Earth-System.

1. The Great Oxygenation Event (GOE):

   As discussed in class the GOE marked the beginning of the swift (at cosmological time scales) evolutionary phase (of the Earth as a whole) triggered by living cyanobactaria which finally lead to formation of multicellular aerobic organisms. This marked the shift from the severe reducing abiotic environment that the earth hosted during it's early stages to the oxygen rich bio-diverse planet we live on.



This, along with several other events in the earths past are not only great examples of how the Earth's atmospheric composition depends on several biological factors; but it also points how such a rapid developmental period in a planet's history might be a key to existence of life itself (more on this in the coming section).

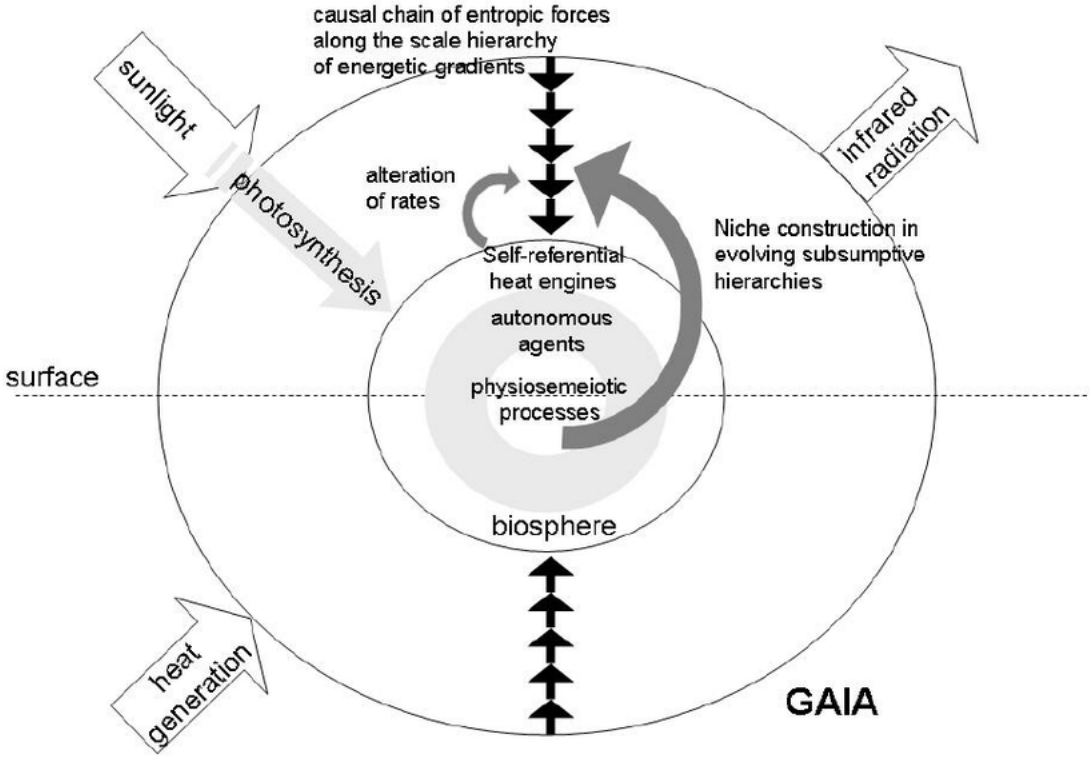
2. The Earth's atmosphere, Carbon Cycle:

   There is strong evidence that no abiotic negative feedback mechanism can explain the stable homeostatic state reached by the Earth-System without biological feedback mechanisms. The participation of living organisms in the Carbon cycle is one of the complex processes that maintains conditions suitable for life. The only significant natural source of atmospheric carbon dioxide (CO2) is volcanic activity, while the only significant removal is through the precipitation of carbonate rocks. Carbon precipitation, solution and fixation are influenced by the bacteria and plant roots in soils, where they improve gaseous circulation, or in coral reefs, where calcium carbonate is deposited as a solid on the sea floor. The stability of several such components of the Earth's atmosphere is controlled by intricate negative feedback mechanisms with major biological contribution. For instance, one of these organisms is Emiliania huxleyi, an abundant coccolithophore algae which also has a role in the formation of clouds. CO2 excess is compensated by an increase of coccolithophoride life, increasing the amount of CO2 locked in the ocean floor.

   One unfortunate example in terms of how life on earth regulates the atmospheric conditions is us humans. We have severely affected several of nature's feedback mechanisms which played a major role in maintaining the stable homeostasis. This is evident from many observations such as the several species extinctions we have witnessed in the short period of our existence on the planet. The Gaian theory predicts that the rate at which humans are affecting the Earth-System; the Ice-age/glaciation cycle

will be disrupted so severely that, if we continue on this trajectory, the inter-glacial period we are in today may extend well beyond the historical (∼50000yrs), if it were to ever occur again that is.

3. Gaian Temperature Regulation:



Interpretations of the Gaia Theory:

There are several prevalent interpretations of the theory. At one end of this spectrum is Weak Gaia: the undeniable statement that the organisms on the Earth have altered its composition and continue to do so. On the other, is considering Earth system as a single living entity called Gaia (even capable of reproducing by colonizing other planets, some argue). In my opinion, the latter interpretation is so radical that it acts as a roadblock when it comes to people appreciating the true potential and beauty of the theory. Whereas the so-called Weak Gaia is quite obvious and not nearly as profound. In my opinion finding a middle ground between these extreme interpretations allows one to fully appreciate the idea. My opinion on this is that the calling Gaia system as a living entity is a drastic step; rather one should stick to considering it as an extremely

complex self-sustaining system consisting several feedback mechanisms between different subsystems which help maintain its state of homeostasis. Even the modern form of the theory takes somewhat of a conservative stance when it comes to considering Gaia as a living entity.

3 The Gaia Bottleneck Hypothesis

With a short section on what exactly is Gaia Hypothesis, we now move to the most interesting part of this report.

We now know that earth like planets-the so called "habitable" planets from the physics and chemistry point of view are not a rarity in our cosmic neighbourhood but presence of life sure is. The most common explanation for this is a low probability for the emergence of life (called an emergence bottleneck), which is thought to arise due to the intricacies of the molecular recipe. There are some other bottlenecks which had been suggested to be the deciding factors in the evolution of life on a wet, rocky planet. Many of these have now been ruled out.

1. No stellar bottleneck: observations have revealed that sun like stars and earth like planets are a commonplace in the cosmos. Not only are planets in the optimal Goldilocks's zone common but also atmospheric spectroscopy reveals many have liquid water.

2. No chemical ingredients bottleneck: recent observations by advanced telescopes have revealed that the chemical ingredients thought to be the key for organic life: hydrogen, oxygen, carbon, nitrogen, sulfur, and phosphorus("HOCNSP") are also a abundantly available in stellar gas clouds, novae etc.

3. There clearly isn't an energy bottleneck because of the abundant photon energy available to many planets of interest.

Many scientists all over the world believe that given the "right" conditions it is more likely than not that life evolves on the planet. Whether it is able to sustain for long without going extinct is another question altogether, and clearly the answer to this seems to be a no. We now look at the alternative Gaia bottleneck explanation which says that if life emerges on a planet, it only rarely evolves quickly enough to regulate greenhouse gases and atmospheric radiation (reflection and absorbtion), thereby maintaining surface temperatures compatible with liquid water and habitability. Such a Gaian bottleneck suggests that (i) **extinction is the cosmic default** for most life that has ever emerged on the surfaces of wet, terrestrial planets in the Universe and; (ii) **terrestrial planets** need to be inhabited to remain habitable. In the Gaian bottleneck model, the maintenance of planetary habitability is a property more associated

with an unusually rapid evolution of biological regulation of surface volatiles than with the luminosity and distance to the host star.

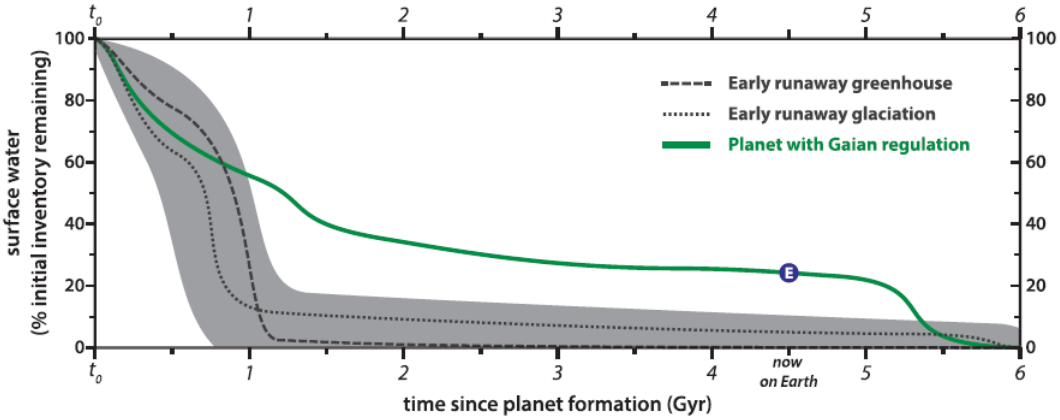
Along with ruling out of the above bottlenecks one other reason to think in a different direction is that without significant abiotic negative feedback mechanisms, the surface environments of initially wet rocky planets are volatile and change rapidly without any tendency to maintain the habitability that they may have temporarily possessed as their early unstable surface temperatures transit through habitable conditions. This motivates one to think of other reasons preventing sustained existence of life on planets. I'll reiterate that of course, an emergence bottleneck is not yet ruled out though others stated above are highly unlikely. But the point of view of many scientists is that on any such earthlike planet facing none of the bottlenecks stated above the probability of emergence is high.

Gaian bottleneck model revolves around the concept of Gaian regulation. It says that life (on Earth and elsewhere) is not just a passive passenger but comes under strong selection pressure to actively modify and regulate its environment. The emergence of life's abilities to modify its environment and regulate initially abiotic feedback mechanisms could be the most significant factor responsible for life's persistence on Earth. If there is anything special about what happened on Earth to allow life to persist here, it might have less to do with the earth being in the so called "habitable" Goldilocks's zone, or due special chemistry, or sources of free energy, or even a rare recipe for the emergence of life. The existence of life on Earth today might have more to do with the unusually rapid biological evolution of effective niche construction and Gaian regulation in the initial stages of earth's life.

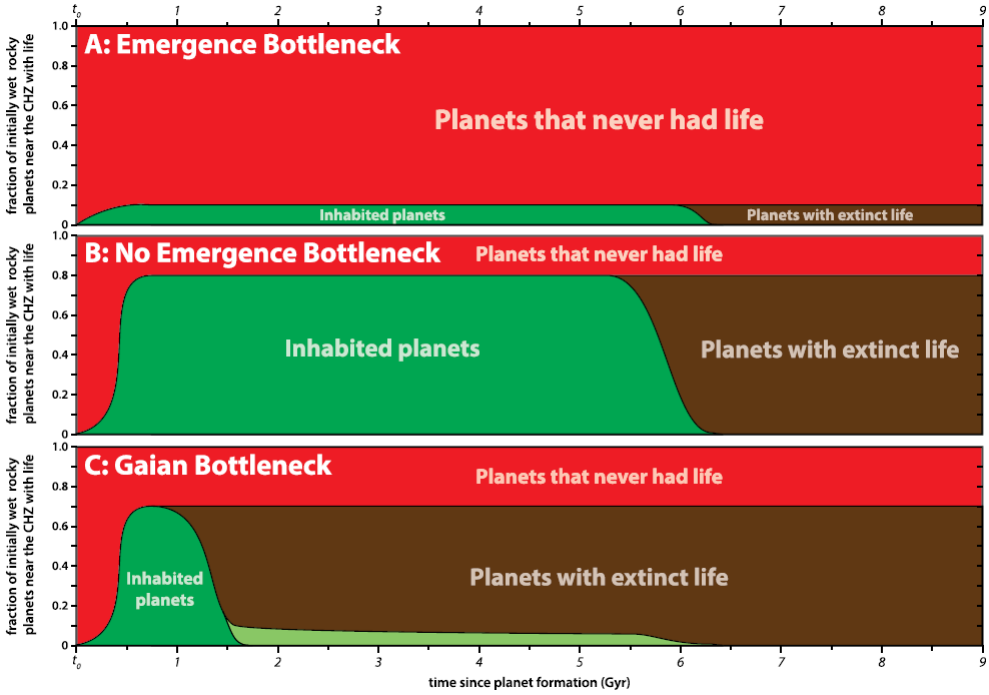
Habitability and habitable zones would then not only be a passive abiotic property of stellar and planetary physics and chemistry but would also be a result of early life's ability to influence initially abiotic and geo-chemical cycles and turn them into the life-mediated bio-geo-chemical cycles that we are familiar with on the Earth today. Thus, coupled with all the abiotic factors it is proposed that Gaian Regulation plays a major role in stabilizing a planet's atmospheric conditions, temperature. Not only that but the Gaian biochemical feedback mechanisms play a huge role in preserving liquid and atmospheric water on a planet's surface.

After a planet's formation the major sources of water are distant icy solar system objects that collide or flyby. Liquid water is not easy to maintain on a planetary surface. The initial inventory of water is lost to space due to a runaway greenhouse, or frozen due to ice-albedo positive feedback. The former is what most likely happened on earth's twin Venus and the latter is what is Mars' current state. However, even though all three of these planets are

theoretically could have sustained water at some point in their life only Earth has managed to do so. Given below is a graph portraying how a Gaian regulated planet would preserve atmospheric greenhouse gases and water differently from a similar planet with only abiotic feedbacks:



The graph shown below compares planets in the CHZ (circumstellar habitable zone) with respect to time span after formation and divides them into three categories based on what bottleneck (if any) is at play:



The Gaian bottleneck hypothesis is fascinating; but what experimental /observational proofs might one look for to support or invalidate this? Also, What might rule out an emergence bottleneck in favor of a different approach towards the answer "why is Earth special?" ? One fascinating way would be the discovery of remnants of extinct microscopic life on Mars. This would majorly be in support of presence of a Gaian regulated mechanism at play. Whereas, discovery of extant life on Mars would be in support of neither. So such hypotheses and theories can only be confirmed or falsified by expanding the horizon of observational capabilities.

4 References

Due to limited amount of time I couldn't cover the various parameter charts and models that make predictions for a Gaian regulated system along with other bottlenecks but I've pasted the link to the paper I read regarding the same and some other resources used.

1. `https://courses.seas.harvard.edu/climate/eli/Courses/EPS281r/Sources/Gaia/Gaia-hypothesis-wikipedia.pdf`
2. The Paper: Chopra, Aditya; Lineweaver, Charles H. (2016). The Case for a Gaian Bottleneck: The Biology of Habitability. Astrobiology, 16(1), 7–22. doi:10.1089/ast.2015.1387
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